

A TEXTBOOK FOR CERAMIC ENGINEERS

by

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It was with pleasure and an appreciation of the work done by Professor Kirkendale, that the Ceramic Association of New York financed the publication of "A Textbook for Ceramic Engineers".

Those who have been acquainted with the first edition, which was published in 1948, will note numerous changes and improvements.

It is the belief of members of the Association that not only students but also plant engineers will find much material of value contained therein.

TABLE OF CONTENTS

	Page
Introduction	vii
Chapter	
1. Classification of Clays	1
2. Ceramic Raw Materials	6
3. The Mineralogical Composition of Clays	14
4. Chemical Composition of Clays	22
5. Chemical Notation and Constitution of Ceramic Materials	26
6. Physical Properties of Clay	34
7. Scumming and Efflorescence	69
8. Distribution of Clay Deposits	73
9. Drying Clays	76
10. Firing Clays	82
11. Washing, Refining, and Beneficiation of Clays and Other Ceramic Materials	90
12. Screening and Lawning	94
13. Classification with Water	106
14. Magnetic Separation	112
15. Crushing and Grinding	116
16. Clay Feeding and Proportioning	144
17. Mixing, Kneading, and Tempering	149
18. De-Watering	155
19. Clay Forming	158
20. Flotation	181
21. Prospecting for Clay Deposits, Collection and Preparation of Samples	184
22. Property Survey	188
23. Winning Clays	193
Index	209

Chapter 1

CLASSIFICATION OF CLAYS

It has been stated that clay is an aggregate of minerals, more or less complex in nature, with widely varying physical and chemical properties. To understand thoroughly the behaviour of clay when processed into a ceramic product, we must first understand the nature of the individual minerals that contribute to the characteristic properties exhibited by the different types of clays.

The complexity of most clays is due to the fact that they occur as a by-product from the weathering and disintegration of feldspars and silicate rocks. Therefore they contain many unweathered minerals that originally occurred in the rock from which the clay was formed. Some clays may be more or less purified by nature and others will contain undesirable as well as desirable accessory minerals. Therefore a study of the properties of clays can be somewhat simplified by classifying them as to their origin as well as their physical properties. Several different bases for classification exist. Ries' classification, based on the geology of the clays, is given below.

A. Residual clays. (Decomposition of rocks in situ.)

I. Kaolins and china clays. (White-burning.)

- a. Veins derived from pegmatite.
- b. Blanket deposits from areas of igneous or metamorphic rock.
- c. Pockets in limestone as Indianaite.

II. Red-burning residuals derived from different kinds of rock.

B. Colluvial clays. Represent deposits formed by wash from residual clays. May be either refractory or non-refractory.

C. Transported clays.

I. Deposited by water.

- a. Marine clays or shales. Deposits often of vast extent.
 1. White-burning clays, ball clays.
 2. Fire clays and shales, buff burning.
 3. Impure clays and shales; calcareous and non-calcareous.
- b. Lacustrine clays. Deposits in lakes or swamps.
 1. Fire clays and shales.
 2. Impure clays and shales; red-burning.
 3. Calcareous clays, usually of surface character.
- c. Flood-plain clays. Usually impure and sandy.

d. Estuarine clays, deposited in estuaries. Mostly impure and finely laminated.

II. Glacial clays. Found in drifts, and often stoney. Red- or cream-burning.

III. Wind-formed deposits. Loess.

IV. Chemical deposits. Some flint clays.

Residual clays are those clays that are found in place, where they were originally formed from the weathering and alteration of the parent feldspathic rock. They are, therefore, usually contaminated with a large amount of unweathered rock, silica grains, and other minerals more or less resistant to the action of weathering forces. The quartz and feldspar grains are usually sharp and angular in form and the deposit may contain as little as 10% or as much as 90% clay matter. Often, underlying beds of residual clays, can be found veins or blanket deposits of the unaltered rock from which the deposit was formed.

The most valuable of the residual clays are the kaolins or china clays. These are relatively pure, white-burning clays that are used extensively in the ceramic whiteware industries. Large veins of pegmatite having become exposed to continuous frost action in winter and heat in summer, and to the chemical action of ground acids and other weathering agents, have changed chemically to form veins of kaolin. Other deposits cover large areas and were formed by the weathering of blanket deposits of igneous rock.

The red-burning residual clays contain more impurities and are not as valuable as the kaolins. They are used chiefly for making building brick and other structural clay products.

Colluvial clays are quite similar in nature to the residual clays since they are merely residual deposits that have been moved a short distance by landslides or heavy rains. An examination of the area will usually disclose the original rock nearby.

Transported clays represent, by far, the majority of clay deposits. Clays may be moved from the location in which they are formed by a number of agents. As these clays are moved a sorting action usually takes place whereby the heavier particles such as coarse quartz and feldspar grains are dropped along the way and only the finer grains and lighter clay minerals are carried away and finally deposited, to form large areas of more or less purified clays. The chief transporting agent for clays is water. Rivers passing through a residual clay bed will pick up the material and carry it along dropping out progressively smaller and lighter particles as the current diminishes in velocity. If the river empties into the sea, the fine clay minerals will be carried out by ocean currents and deposited over a very large area; the finer particles the farthest from the mouth of the river. Thus, very pure and high grade deposits are formed. Some kaolins, some fire clays and most ball clays are found as marine deposits. Sometimes marine deposits are contaminated with lime. These are

known as calcareous clays. Shells of sea creatures become inter-mixed with the clay causing it to lose its high quality of refractoriness and to be non-uniform in its physical properties. Silt and iron-bearing minerals may become mixed with the clay. Such clays lose their value as a raw material for the better grade ceramic ware but may be used for making structural clay products.

In a similar manner clays may be deposited by rivers into large or small lakes. These are known as lacustrine deposits and are usually of poorer quality than the marine clays. This is so because the smaller body of water restricts the natural sorting action. Other water-transported clays are those that have been built up in layers in flood plains. As rivers overflow their banks in times of flood clay, silt and other debris will be deposited in the plains along the river banks. Estuarine deposits are those clays that have settled out in an arm of the sea. Both flood-plain and estuarine clays tend to be of an impure nature.

Glacial clays are clays which have been moved by glacial ice. Thousands of tons of ice, moving across the land during periods of glaciation, will pick up clay, earth, silt and boulders and carry this glacial moraine for hundreds of miles. As the ice melts this material will be left behind in vast quantities. Glacier-deposited or boulder clay is often so contaminated with everything from rock flour to large boulders that it is of no value in the ceramic industries. Boulder clays are used, however, to a limited extent for structural clay products.

Clays transported by wind are fine grained materials of relatively minor importance in ceramics.

A very useful way of classifying clays is in the order of their purity and refractoriness.

Residual kaolins are kaolins found in place, usually associated with the parent or unaltered rock. They have a melting point of about cone 34, or 1760°C . The alkali content is at a minimum, and at least feeble plasticity has been developed. The primary mineral of kaolin is "kaolinite" ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$), but residual kaolins are often associated with unaltered quartz and mica. Residual kaolins are usually coarser grained and have less plasticity than transported kaolins.

Secondary kaolins are kaolins which have been transported by streams from the place in which they were formed, and deposited in lakes or sheltered arms of the ocean. They will vary considerably in purity. Some of the Georgia beds contain as high as 99% clay material, while those of Florida yield as low as 25% kaolin on purification. Kaolin strata are sometimes interbedded with sands and limestone. Secondary kaolins are usually finer grained and more plastic than primary kaolins and, like the primary kaolins, they have a melting point of about cone 34.

Ball clays are also of high purity and refractoriness; cone 30 to 33 (1650° to 1745°C .). Like kaolins, they are white- or light-cream-burning

clays, but have the highest degree of plasticity of all clays. Ball clays are light-gray to black in color, generally due to fine organic material associated with them. When fired, this organic material burns and their characteristic cream to white color remains. Ball clays represent the finest of clay substances which will float the longest time in quiet lakes or seas. Ball clays are usually mixed with kaolin in a ceramic whiteware body to increase the plasticity and workability, and to improve the dried and fired strength of the body.

Flint fire clays are hard, dense, highly aluminous, flint-like clays which, in the original condition, break with a conchoidal fracture. Their plasticity is very low, but may be partially restored by persistent grinding with water. Flint fire clays are refractory with a melting point of cone 30 to 33 (1650° to 1745°C.). They are similar to ball clays in composition, color, and firing properties, but represent a hardened or set gel condition of what was formerly very finely divided, plastic clay substance. They burn to a buff or light-brown color and are used, either alone or in combination with some of the more plastic fireclays, for the manufacture of high-quality refractories.

Plastic fire clays vary in plasticity from moderately-plastic to highly-plastic clays and in refractoriness from third-quality fire clays, cone 18 to 28 (1485° to 1615°C.), to second-quality fire clays, cone 29 to 30 (1640° to 1650°C.), to first-quality fire clays, cone 31 to 33 (1680° to 1745°C.). They are more widespread in occurrence than kaolins, ball clays and flint fire clays, and are used in manufacturing a wide variety of refractory materials.

Low-refractory buff-burning clays have a melting temperature or fusion point ranging between cone 6 (1190°C.) and cone 19 (1515°C.). They usually contain an excess of quartz, feldspar, and mica with small quantities of lime, magnesia, and iron oxide. Their fired color ranges from light buff to salmon red; the red color being imparted by some form of iron oxide. The more iron-bearing minerals the clay contains, the darker will be the shade of red, except in the case where the clay also contains a high quantity of lime, which tends to counteract the red color imparted by the iron. They are used chiefly for making buff-burning structural brick and tile, architectural terra cotta, and various forms of pottery, such as stoneware, mixing bowls, and sometimes art pottery.

Shales are clays which have become hardened and stratified by heat or pressure, or both. Shales are more or less plastic, depending upon the degree of weathering to which they have been exposed. Deep-lying shales are usually very hard and often slate-like, with little plasticity. Surface shales may be so weathered that they become soft and friable, and have developed good plasticity. Most shales contain sufficient iron oxides or iron-bearing minerals to burn to a red or brown color; a few are buff-burning. Their melting point varies between cone 01 (1110°C.) and cone 10 (1260°C.). When clay is changed

to shale under the influence of pressure and heat, part of its combined water is expelled. This results in a partial loss of plasticity for the shale, which may be recovered, to a certain extent, by grinding in water or by proper weathering. Shales are used chiefly for making structural brick and tile.

Bedded clays are soft clays which have not been hardened into shales, but show lamination planes due to having been deposited by sedimentation in water. They usually have good plasticity and workability when mixed with water, and have a fusion point between cone 01 (1110°C.) and cone 5 (1180°C.). They are generally impure clays which fire to some shade of red, and are excellent clays for structural brick and tile.

Alluvial clays are flood-plain clays which have been deposited along river channels. They have a low melting temperature, are buff- to red-burning, have fair plasticity, and are satisfactory material for making structural brick.

Glacial clays are surface clays which have been left by retreating glaciers. Glacial deposits represent a varied mixture of materials, often containing a large amount of pulverized rock flour with unleached feldspar and basic minerals in but slightly altered condition. They usually contain many pebbles and stones, which must be removed before the clay can be used. These are the poorest types of clays. Due to their many impurities they have poor plasticity, a short vitrification range, poor fired color, and a low fusion point; cone 010 (890°C.) to cone 4 (1165°C.). Their chief use is in the manufacture of common brick.

Loess is wind-blown clay found chiefly in arid regions. It is often found in great beds of considerable thickness. It is used to a small extent in making common red-burning structural wares.

Aluminous allied materials such as bauxites, diaspores, and other high alumina ceramic raw materials, while they do not strictly come under the classification of clays, are nevertheless of high value in making special refractories. The fusion point of such materials will be between cone 33 and cone 36 (1745° to 1810°C.).

An attempt has been made in the foregoing to classify clays both with respect to their geological history and according to their value and use in the ceramic industries. The purer, more highly refractory clays occur less frequently and command a higher market price than the more common impure clays.

Chapter 2

CERAMIC RAW MATERIALS

Materials used in compounding ceramic bodies cover a very wide range of substances, organic and inorganic, metallic and non-metallic. Clays, of course, are the most important and chief raw materials in the large majority of ceramic bodies. The importance, however, of non-clay materials to the science of ceramics cannot be overlooked. Because a considerable number of the less common non-metallics have come into use in the ceramic industry in recent years and are not yet widely used, many ceramic engineers do not realize how extensive the list has become. Virtually any substance whatsoever has a possibility as a useful raw material in a ceramic body and although the use of nonmetallics has expanded tremendously in the past few years, and many raw materials have been investigated for their use as an addition to a ceramic body, many more have yet to be tried.

The following is only a partial list of the more commonly used ceramic raw materials.

Kaolin. The name kaolin is supposed to have come from two Chinese words, "Kao - liang" meaning "high ridge", a local designation for the area in which a white china clay was found. Today the terms kaolin and china clay are often used interchangeably to describe a specific group of clays composed principally of the mineral kaolinite, and characterized by their ability to fire to a white or near-white color and by their refractoriness, which is in the range of cone 33 to cone 35.

Chosen primarily for their good white color when fired, kaolins are not strong; ball clay is added to the body to give it strength in the unfired state. Secondary kaolins usually have greater plasticity and higher strength than residual kaolins. Kaolins are an integral part of white ware body mixtures and different kaolins impart different characteristics to a body. It is often advantageous in compounding a ceramic body to use two or more different kaolins in definite relative proportions to obtain the most satisfactory physical properties in any particular ceramic body. While American kaolins differ somewhat in themselves, a wider variation of properties will be found between American kaolins and English kaolins. The essential properties in which the English kaolins and most of the comparable American clays differ are (1) refractoriness, (2) color, (3) strength, after low-temperature heat treatment, (4) linear thermal expansion, and (5) shrinkage and porosity after heat treatment at all temperatures.

These differences usually can be traced primarily to fundamental differences in equivalent mineral compositions and secondarily to differences in the amount of fine-grained material present.

The following table gives analyses of several different kaolins:

	Georgia Kaolin	N. Carolina Kaolin	English Kaolin	Florida Kaolin	Alabama Kaolin	Theroetical Kaolin
Silica	45.3	46.3	47.0	46.3	44.7	46.3
Alumina	39.1	38.8	37.7	37.7	39.5	39.8
Titanium						
Oxide	1.5	0.1	0.2	0.5	1.3	
Iron Oxide	0.3	0.4	1.0	0.8	0.6	
Lime	0.1	0.1	0.2	0.5	0.0	
Magnesia	0.1	0.1	0.2	0.0	0.0	
Potash	0.2	0.3	1.6	0.2	0.0	
Soda	0.1	0.2	0.2	0.0	0.0	
Water	<u>13.7</u>	<u>13.7</u>	<u>12.4</u>	<u>13.7</u>	<u>13.9</u>	<u>13.9</u>
	100.4	100.0	100.5	99.7	100.0	100.0

It will be observed that kaolin usually contains less than 2% combined potash and soda, and that the moisture content is remarkably uniform. It is characteristic of high-grade kaolins that the water content is approximately 13.9%. The amount of impurities present should not be high. Too large an amount of titanium oxide will cause the kaolin to fire to a grey or off-white color. Iron oxide imparts a red color to the fired body and should not be greater than 2% in the analysis of the clay, for most purposes. Potash and soda, if present in too great a quantity, will lower the fusion point of the clay and cause vitrification at lower temperatures. In many whiteware bodies, however, potash and soda are deliberately added for this purpose.

Ball clay. The term ball clay is applied to a large group of sedimentary, highly-plastic, refractory clays which are mostly dark in the unfired state, due to organic matter, but which fire to a creamy white. In composition, ball clays greatly resemble kaolin in that kaolinite is the principal clay mineral present. The ball clays, however, usually contain a greater variety of impurities, such as iron, titanium, lime, alkalies, and considerable organic matter.

The name for this class of clays is derived from old English practice where the clay was taken from the pit in the form of balls, weighing about 33 pounds each.

Ball clay is widely used in white ware bodies for two primary reasons: (1) to improve the plasticity and castibility and (2) to increase the strength of the article both in green and fired states. Ball clay also aids in the vitrification of the body because the fluxes present are of extremely fine particle size and evenly distributed throughout the clay. Because of their high plasticity, ball clays also have high shrinkage and, therefore, the shrinkage of a ceramic body

tends to increase with increasing ball clay content. Analyses of some domestic ball clays are given below:

	Kentucky No. 4	Kentucky No. 12	Dresden	Champion	Tennessee Royal
SiO ₂	51.7	47.4	54.0	52.3	49.0
Al ₂ O ₃	31.2	31.0	30.7	30.4	29.1
TiO ₂	1.7	1.7	1.1	1.7	1.7
Fe ₂ O ₃	1.2	1.1	1.6	1.0	0.7
MgO	0.5	0.6	0.5	0.1	0.0
CaO	0.2	0.2	0.4	0.1	0.1
K ₂ O	0.4	0.1	0.3	0.3	1.7
Na ₂ O	0.6	0.4	0.3	0.1	0.5
L.O.I.	<u>12.1</u>	<u>17.4</u>	<u>11.5</u>	<u>14.1</u>	<u>17.0</u>
	99.6	99.9	100.4	100.0	99.8

The difference in chemical analysis between typical ball clays and kaolins can be readily compared. Ball clays tend to be higher in SiO₂ and lower in Al₂O₃ content than kaolins. Most impurities are present in larger quantities which accounts for the slight discoloration in fired ball clays and for their somewhat lower fusion point. The L.O.I., or loss on ignition, includes carbonaceous matter as well as water and this accounts for the large variation in percent L.O.I. in different ball clays.

In normal commercial practice, ball clay is used in approximately the following amounts:

Type of Ware	Percent by Weight Ball Clay
Vitreous sanitary ware	10 - 40
Hotel China	7 - 15
Floor and wall tile	10 - 28
Electrical porcelain	10 - 35
Semi-vitreous whiteware	20 - 45

Fire Clay is a refractory clay with a fusion point of not less than cone 19. It is of sedimentary or residual character, varies in plasticity, and often fires to a buff color, but not necessarily so. The flint fire clays have a dense structure, are hard, and break with a conchoidal fracture. They are difficult to slake and have little plasticity under usual working conditions. Flint fire clays are often blended with plastic fire clays and act as a natural grog. Fire clays are used chiefly for the manufacture of refractory brick and shapes. The clay deposits are usually of sedimentary origin and are often associated with coal measures. Chemical analyses of some American fire clays follow:

	Ohio		Pennsylvania		Denver	Missouri
	Plastic	Flint	Plastic	Flint		
SiO ₂	55.5	59.9	62.0	54.7	46.9	61.2
Al ₂ O ₃	28.3	27.6	27.2	30.7	35.4	25.6
Fe ₂ O ₃	2.5	1.0	(	0.1	0.0	0.0
			(0.4			
FeO	0.0	0.0	(	0.0	1.7	1.7
CaO	0.3	0.0	(	0.2	0.4	0.0
			(2.9			
MgO	0.1	0.0	(	0.1	0.2	0.0
KNaO	1.4	0.7	0.0	0.1	1.2	1.3
L.O.I.	11.4	10.8	7.5	14.0	14.1	9.7
	99.5	100.0	100.0	99.9	99.9	99.5

Common Clays vary widely in their composition and physical properties, due to their varied content of impurities. They have a low fusion point and fire to a buff, salmon or red color. Properties of common clays most useful to the structural clay industries are good plasticity, workability, a long firing range and a good fired color. The better grade of common clays are the most desirable but some very poor clays are successfully being used for making bricks. A good shale with sufficient plasticity is often preferred to clay for making brick and tile. Typical analyses of some common clays and shales are:

	Red burning Glacial Clay	Lorraine Shale	Common Clay I	Common Clay II
SiO ₂	69.1	59.2	58.5	47.5
Al ₂ O ₃	14.0	18.4	17.0	13.7
Fe ₂ O ₃	4.8	5.4	5.5	4.4
CaO	1.9	3.3	6.4	15.6
MgO	1.1	3.3	2.2	0.8
K ₂ O	3.6	1.6	3.0	1.6
Na ₂ O	0.0	0.0	2.2	2.8
L.O.I.	4.8	9.2	3.4	12.9
	99.3	100.4	98.2	99.3

The wide difference in composition in common clays can readily be seen from the above analyses. The Al₂O₃ content is much lower than that in the higher grade clays. The SiO₂ content is higher because more free quartz is present. The low percent of Al₂O₃ means low refractoriness. It can also be noted that the iron content is high. An iron content of 5 percent or higher produces a good red fired color in ware made from the clay. This is true for all of the above clays except common clay II. In this case the CaO or lime in the amount of 15.7 percent will mask the red color due to iron and the fired product will be a buff color.

Bentonite is a natural, inorganic material composed chiefly of montmorillonite ($\text{Al}_2\text{O}_3 \cdot 4 \text{SiO}_2 \cdot 9\text{H}_2\text{O}$) and is usually derived from volcanic ash. The material has extremely fine particle size and has the characteristics of colloids. The chief value of bentonite lies in its extreme plasticity. For many commercial bodies, a two percent addition of bentonite improves the plasticity more than the addition of ten percent of ball clay. Because of its colloidal nature, it is used as an adsorptive material in refining oils and gasoline.

Flint is the term applied to finely pulverized powder, made of white quartzite sand. Chemically, the material is pure silica, SiO_2 . It is non-plastic in unfired bodies, and by its addition the workability and drying shrinkage of the body are lowered, and drying behavior improved. In the fired body, flint adds strength, toughness, and hardness. Flint is mined in Illinois, West Virginia, and Pennsylvania.

Feldspar is the broad name applied to a group of alkali-aluminosilicate minerals, most important of which are microcline, orthoclase, and albite. The first two are potash spars and contain about 16.9 percent K_2O , while albite is a soda spar and has 11.9 percent Na_2O , plus some iron oxide, free quartz, and traces of magnesia. Many feldspars also contain small amounts of lime spar or anorthite. North Carolina normally produces about half the annual output of feldspar in the United States, the balance coming from Maine, South Dakota, New Hampshire, Colorado, and California.

Feldspar is universally used in whiteware bodies as a flux. As the temperature increases when a ceramic body containing feldspar is being fired, the feldspar becomes active, dissolving first the clay minerals and finally the flint particles. In the fired body, feldspar increases the coefficient of thermal expansion, gives high strength with minimum absorption, and improves the translucency. The following table indicates the range of amounts of spar commonly used in various types of bodies:

<u>Type of Ware</u>	<u>Percent of Spar</u>
Sanitary Ware	25 - 35
Hotel China	15 - 35
Chemical porcelain	15 - 30
Semi-vitrous chinaware	15 - 30
Floor and Wall tile	10 - 55
Electrical porcelain	30 - 45

Nepheline syenite is an igneous rock composed chiefly of nepheline ($\text{K}_2\text{O} \cdot 3\text{Na}_2\text{O} \cdot 4\text{Al}_2\text{O}_3 \cdot 9\text{SiO}_2$), microcline, and albite. It is used mainly as a flux, and may replace part or all of the feldspar in a body. It begins to melt at cone 02, has a fusion point of about cone 7, and has a melting range from 1095°C . to 1210°C . In unfired bodies, nepheline syenite behaves similarly to feldspar but, due to its fluxing action at lower temperatures, it lowers the firing temperature of the

ware. It increases the firing range, increases strength, and decreases absorption as compared with bodies containing feldspar as a flux.

The chief source of nepheline syenite is near Lakefield, Ontario, Canada.

Talc is a naturally occurring magnesium silicate. Ceramic grades of talc are produced chiefly in California, New York, and Nevada.

Talc is used, in moderate amounts, in such ceramic bodies as artware, tile, dinnerware, and sanitary ware. Larger amounts are used in high-frequency dielectric bodies, because of the favorable effect on electrical properties. Talc is used for the fluxing action of the MgO it contains; it lowers the moisture expansion of porous bodies, thereby decreasing delayed crazing of the glaze; and it reduces the workability of plastic bodies.

Pyrophyllite is a soft mineral of the aluminum silicate groups, with the formula $Al_2O_3 \cdot 4SiO_2 \cdot H_2O$. It is used in ceramic bodies to replace all or part of the feldspar. Pyrophyllite does not materially change the shrinkage or absorption of a body, but it lengthens the firing range, increases the fired strength, and reduces the coefficient of thermal expansion.

Spodumene is a lithium-aluminum silicate ($Li_2O \cdot Al_2O_3 \cdot 4SiO_2$) found chiefly in South Dakota, California, Massachusetts and North Carolina. Lithia is a powerful flux, particularly when used in conjunction with feldspar, and proportional mixes of spodumene and feldspar begin to fuse at temperatures much lower than the fusion point of either material alone. Spodumene-feldspar mixtures decrease the porosity of a body and increase the fired strength.

Lepidolite is a lithium-potassium-aluminum fluosilicate, used in the manufacture of certain types of glass and as a flux along with feldspar in ceramic bodies. Lepidolite is often found in association with spodumene.

Lime is usually added to a ceramic body as whiting, a pure calcium carbonate. It is useful as a flux because of compounds it forms with soda and silica. The addition of lime to a body increases the shrinkage and strength, and decreases the porosity.

Beryl, a beryllium aluminum silicate, $BeO \cdot Al_2O_3 \cdot 6SiO_2$, is mined domestically in South Dakota, Colorado, and several of the New England states. Although quite refractory, beryl, when substituted for a part of the feldspar in a ceramic body becomes an active flux. It increases the resistance to thermal shock, increases electrical resistance, increases mechanical strength, and lowers absorption and firing shrinkage.

Bone Ash is the product of calcined bones and is a mixture of calcium phosphate, calcium carbonate and magnesium phosphate. Most of the bone ash used commercially is manufactured as a precipitated $Ca_3(PO_4)_2$. Small amounts of bone ash in a chinaware body act as a flux and give to the body high translucency, but make it very brittle.

Zircon or zirconium silicate, $ZrSiO_4$, when added to a ceramic body, provides an extremely low thermal expansion. It is a valuable ingredient in chemical porcelain and special refractories.

✓ Kyanite, $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$, is added to ceramic bodies to improve the strength, thermal resistance, and spalling resistance of the body. Under heat treatment fine, needle-like, mullite crystals develop and due to their interlocking nature, they provide mechanical strength.

Sillimanite and andalusite are similar in chemical composition and in their reaction in ceramic bodies to kyanite.

✓ Topaz, $(\text{AlF})_2\text{SiO}_4$ when calcined is an excellent substitute for Indian kyanite. It is used in refractories of high-alumina type and may be used as a source of fluorine in raw state in some glasses and enamels.

• Bauxite is a highly refractory material used chiefly as an ore of aluminum, but often used for special refractory brick.

✓ Diaspore, $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$, is used to a large extent for making high-grade refractory brick and shapes.

• Chromite is used in the manufacture of such basic refractory brick as chrome brick.

Magnesite is also used for the manufacture of basic refractories. It is magnesium carbonate, associated with iron and calcium.

Olivene, $\text{MgFe}_2 \cdot \text{SiO}_4$, is used in magnesium silicate or forsterite refractories.

• ✓ Dolomite, $\text{CaMg}(\text{CO}_3)_2$, has a number of important uses in the ceramic industry. As a source of MgO it is useful in the manufacture of basic refractories. Dolomite may be substituted for nearly any other type of lime flux in pottery bodies and glazes. It is used extensively in the manufacture of glass. Dolomite has a powerful fluxing action and a glass containing dolomite is said to fire quicker than one using lime from another source. The most important deposits of dolomite in the United States are in northwestern Ohio, New York, Connecticut, California, Pennsylvania, Missouri, Texas and Kansas.

Antimony oxide is used in glazes, glasses and enamels as an opacifier. Its usual composition is Sb_2O_3 , but may come as Sb_2O_4 or Sb_2O_5 . It does not give color to a glass when added in small amounts, except in the presence of lead, where it will give a yellow color.

Barium carbonate, BaCO_3 , is a very active flux used chiefly in glasses, glazes, and enamels.

Borax, $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$, is used as a flux in glasses, glazes, and enamels. The important oxide introduced is B_2O_3 , which may also be added as boric acid, H_3BO_3 . It is quite soluble and therefore its use is restricted when in contact with water. It is often added to a batch in the form of a frit.

• Cryolite, Na_3AlF_6 , is used as a flux. The fluorides give opacity to silicate bodies.

Fluorspar, CaF_2 , is used interchangeably with cryolite.

• Lead oxides or lead compounds, such as red lead, Pb_3O_4 ; litharge, PbO ; and white lead, $2\text{PbCO}_3(\text{PbOH})_2$, are used as a flux in glasses, glazes, and enamels.

✓ Andalusite, $\text{Al}_2\text{O}_3\text{SiO}_2$, is used principally in spark plug porcelains and special refractories for high temperature service. Along with kyanite and sillimanite it is a mullite-forming mineral.

Dumortierite, $8\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{B}_2\text{O}_3 \cdot \text{H}_2\text{O}$, is also used in the manufacture of spark plug cores and high-grade laboratory porcelain. Dumortierite widens the burning range of the bodies, burns to a pure white, and its fluxes, particularly boron, have a beneficial effect upon the properties of the porcelain produced.

Cadmium sulfide, CdS , is used in glasses and glazes to give yellow colors.

Chromium oxide, Cr_2O_3 , usually gives greens, sometimes light brown.

Cobalt oxide, CoO , gives a strong blue color. It is used in ground coats of vitreous enamels to promote adherence of the enamel to the metal.

Copper oxide, CuO , gives a light blue or blue-green color, which may be reduced in glazes to a deep red.

Iron oxide gives a green, brown, or red color to glazes, and a cloudy green in glass.

Manganese oxide, MnO , gives a brown or purple color.

Nickel oxide gives brown and dark purple colors.

Potassium dichromate, $\text{K}_2\text{Cr}_2\text{O}_7$, usually gives pink shades when associated with tin.

Rutile, TiO_2 , gives a weak greenish-yellow color. It is sometimes used as a body color to obtain ivory.

Uranium oxide, derived from $\text{Na}_2\text{U}_2\text{O}_7$, will give a yellow color.

Vanadium oxide, V_2O_5 , gives a green color.

Binders are sometimes added to ceramic bodies to give additional strength to the unfired body, and reduce loss from breakage in handling. They are usually, but not necessarily, organic compounds which will burn out when the ware is fired. Some of the more commonly used binders are gum tragacanth, gum arabic, dextrin, and sodium silicate.

Gelatin is used as a protective colloid.

Placing sand is sand used to surround chinaware in saggers to prevent warping during firing.

Plaster of Paris is used for making molds for casting ceramic ware.

Rouge is made by roasting iron sulphate, and is used for polishing glass.

Sawdust is sometimes mixed with clay to open it up and give high fired porosity. It is used in making insulating building products.

Sodium silicate is used as a binder and as a deflocculent in casting slips.

Diatomaceous earth is a highly siliceous mineral derived from skeletons of diatoms. It is used for making insulating brick and insulating powder.

Vermiculite is a hydrated biotite mica. It possesses the peculiar property of exfoliating from 16 to 20 times its original size on heating and is used as an insulating material.

Corundum is a natural abrasive used in some coarse grained vitrified bonded grinding wheels and for the grinding of precision optics.

Chapter 3

THE MINERALOGICAL COMPOSITION OF CLAYS

When studying clays from the standpoint of their mineralogical composition, it must be borne in mind that clays are essentially an aggregate of minerals. The most important of these minerals are the clay minerals, which we may call "primary minerals". Most clays are composed essentially of minute particles of one or more of the clay minerals. The clay minerals occur in flake-shaped particles, possess base-exchange capacity, and are reducible to extremely small grain sizes on working with water. These properties are possessed in varying degrees by different clay minerals.

Non-clay minerals or "accessory minerals" associated with clay minerals may be beneficial or harmful to the clay, according to their nature. Certain minerals contribute to the plastic qualities of the raw clay; these are called "plastics". Others are relatively inert and act as an aggregate of grains which are cemented together by the plastic material; minerals of this class are called "fillers". Still other minerals react with clay minerals at high temperatures, causing the whole mass to melt and soften at a lower temperature than it would otherwise do if it were composed of clay minerals alone; these minerals are called "fluxes". Therefore, in many natural clays we have combined a plastic, a filler, and a flux. The following table lists the more common minerals found in clays:

Principal Minerals		Plastic Filler	Hardness	Specific Gravity
Name	Composition	Flux		
1. Kaolinite	$\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	Plastic	1 - 2.5	2.2 - 2.6
2. Allophane	$\text{Al}_2\text{O}_3 \cdot n\text{SiO}_2 \cdot n\text{H}_2\text{O}$	Plastic	3.0	1.8 - 1.9
3. Pholerite	$\text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2 \cdot 4\text{H}_2\text{O}$	Plastic		
4. Halloysite	$\text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	Plastic	1 - 2	2.0 - 2.2
5. Nacrite	$\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	Plastic	2.5	2.5
6. Dickite	$\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	Plastic	2.0	2.6
7. Anauxite	$\text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	Plastic		
8. Endellite				
9. Montmorillonite	$(\text{MgCa})\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 5\text{SiO}_2 \cdot n\text{H}_2\text{O}$	Plastic		
10. Beidellite	$\text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2 \cdot n\text{H}_2\text{O}$	Plastic	1.5	2.6
11. Nontronite	$(\text{FeAl})\text{O}_3 \cdot 3\text{SiO}_2 \cdot n\text{H}_2\text{O}$	Plastic	1.0	2.5
12. Saponite	$2\text{MgO} \cdot 3\text{SiO}_2 \cdot n\text{H}_2\text{O}$			
13. Illite (Bravaisite)				
14. Diaspore	$\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$	Plastic	7	3.3
15. Gibbsite	$\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$	Plastic	3.0	2.4
Primary Accessory Minerals				
16. Quartz	SiO_2	Filler	7	2.6
17. Feldspar - Microcline	$\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$	Flux		
Albite	$\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$	Flux	6	2.54 - 2.57
Anorthite	$\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$	Flux		
18. Amphibole Pyroxenes				
Augite				
Hornblende	$\text{CaO} \cdot 3\text{Mg}(\text{Fe})\text{O} \cdot 4\text{SiO}_2$	Flux	5 - 6	2.9 - 3.2
19. Mica - Muscovite	$\text{K}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot 2\text{H}_2\text{O}$	Flux		
Biotite	$\text{K}_2\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot 2\text{H}_2\text{O}$ plus FeO	Flux	2 - 3	2.8 - 3.1
20. Oxides -				
Magnetite	Fe_3O_4	Flux	6	5.1
Hematite	Fe_2O_3	Flux	6	5.2
Rutile	TiO_2	Flux	6.5	4.3
Ilmenite	$\text{FeO} \cdot \text{TiO}_2$	Flux	6.5	4.8
Chromite	$(\text{FeMg})\text{O} \cdot (\text{Cr.Al})_2\text{O}_3$	Flux	5.5	4.5

Secondary Accessory Minerals		Plastic Filler	Hardness	Specific Gravity
Name	Composition	Flux		
21. Silica				
Opal	SiO ₂	Filler	7	2.6
Chert	SiO ₂	Filler	7	2.6
22. Iron Group				
Limonite	2Fe ₂ O ₃ . 3H ₂ O	Flux		3.7
Siderite	Fe . CO ₃	Flux	4.0	3.8
Pyrite	FeS ₂	Flux	6.5	5.0
23. Lime -				
Calcite	CaCO ₃	Flux	3	2.7
Selenite	CaSO ₄ . 2H ₂ O	Flux	2	2.3
Gypsum	CaSO ₄ . 2H ₂ O	Flux		
24. Magnesia -				
Serpentine	3MgO . 2SiO ₂ . 2H ₂ O	Flux		
Magnesite	MgCO ₃	Flux	4.0	3.0
Dolomite	MgCO ₃ . CaCO ₃	Flux	3.8	2.9
25. Carbon				
Wood				
Peat				
Lignite				
Coal				

Mineralogical analyses of a large number of clays have disclosed three very important groups of clay minerals. These are (1) the kaolinite group, (2) the montmorillonite group, and (3) the illite group. Clays, therefore, generally are composed of a member or members of the three groups along with certain non-clay minerals.

Kaolinite is the most important member of the kaolinite group and is found in most clays. It contains 39.8 percent Al₂O₃, 46.3 percent SiO₂ and 13.9 percent H₂O. It is crystalline, belonging to the monoclinic system. It has a hardness of 1 to 2.5 and a specific gravity of about 2.6. It is white when very pure, but frequently slight traces of color are evident due to impurities. It is insoluble in water, but can be dissolved in sulfuric acid. The effect of heat on kaolinite is to drive off the water of hydration at comparatively low temperatures. The resultant product is hygroscopic and will reabsorb the water if the heat treatment is not too high. It is very highly refractory, and has a melting point of 1760°C. It slakes or breaks down readily in water. Kaolinite is formed by weathering or pneumatolysis from feldspathic or similar rock by the following reaction:



Montmorillonite. The group takes its name from the mineral montmorillonite ($\text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot n\text{H}_2\text{O}$). Montmorillonite usually contains magnesium. Beidellite, with a lower silicon and higher aluminum content, and nontronite, in which the aluminum has been replaced by ferric iron, are members of this group. Another member of the group is saponite in which the aluminum has been completely replaced by magnesium.

Illite. This group includes the abundant and widely distributed clay minerals which are similar but not identical with muscovite. Clay minerals in the illite group contain magnesium and iron replacing some of the aluminum.

Montmorillonite, illite, and kaolinite have pronounced basal cleavage, which takes place with relative ease between the structural units composing them. Fragments of these minerals are therefore flake-shaped, and clays may be looked upon as aggregates of flake-shaped particles. Breakage along the cleavage surface takes place more readily in the montmorillonite minerals than in the kaolinite minerals. The former minerals exist in, or can be easily broken down by working with water to, a smaller particle size than the latter. Analysis of numerous samples of illite indicate that this property is variable for members of this clay-mineral group. Some illites can be broken down easily by working with water whereas others exist in larger particles and are not easily reduced in size by similar working.

Halloysite. This mineral is comparatively rare. It is amorphous, has little plasticity and tends to swell when placed in water. Otherwise its properties are quite similar to kaolinite.

Pholerite. This mineral is rare. It resembles kaolinite in its general properties, being a white crystalline material of high plasticity.

Allophane is very rare. It resembles kaolinite in its general behavior.

Aluminum hydroxides. There are three aluminum hydroxides: diaspore ($\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$), bauxite and gibbsite ($\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$). Diaspore is the most important. It is not very common in clays, but beds of diaspore occur in Missouri mixed with flint clay. It has low shrinkage and very high refractoriness. Bauxite is an important ore of aluminum. Gibbsite has a theoretical importance as a building unit in the clay molecule.

Quartz is usually present in clays and is a very important constituent of ceramic bodies and glazes. It is crystalline, belonging to the hexagonal system. It is very refractory and acts as a filler in a ceramic body. It melts at 1725°C . and expands on being heated. The expansion is caused by the formation of tridymite and cristobalite which have lower specific gravities. Quartz is very resistant to the weathering agencies.

The Feldspars. There are a number of feldspars which differ from one another in detail, but all of them are compounds of alkalis or alkali-earths with alumina and silica. Microcline or potash

feldspar ($K_2O \cdot Al_2O_3 \cdot 6SiO_2$) is the most common and important member. In another crystal form it is called orthoclase. It is crystalline, belonging to the monoclinic system. In the pure state it is white, but usually enough impurity is present to give it a color. It melts at about $1250^{\circ}C$. and acts as a flux in a ceramic body. The soda feldspar, albite ($Na_2O \cdot Al_2O_3 \cdot 6SiO_2$), and the lime feldspar, anorthite ($CaO \cdot Al_2O_3 \cdot 2SiO_2$), are fairly common fluxes in ceramic bodies.

The amphibole-pyroxenes. There are a large number of members of this group. Inasmuch as these minerals contain iron, they are colored and heavy. For the same reason, they are disintegrated by weathering very easily and are very rare in clay. These minerals function as fluxes.

Muscovite. This material is very common in some clays. Some clay deposits have been formed almost wholly by the weathering of muscovite. Muscovite is almost transparent and tabular in structure. It has a highly perfect basal cleavage, permitting thin, elastic leaves to be split off. It does not weather very readily and therefore is very common in clays. It functions chiefly as a filler, but also exerts a fluxing action.

Biotite. The iron content of biotite gives it a black color. Its structure and appearance are similar to muscovite. It has a comparatively low melting point and functions as a flux. It is very common in igneous rock, but rare in clays. Its scarcity in clays is due to the ease with which it weathers.

Rutile. This is a crystalline material, usually brown in color. It is not common in clays, but when present gives a gray fired color to white-burning clays. It weathers with great difficulty, so that any rutile occurring in the igneous rock from which the clay is formed usually occurs in the clay. It has a slight fluxing effect.

Ilmenite. This is a dark-colored heavy mineral which weathers readily to limonite and rutile. For that reason, it rarely occurs in clays.

Magnetite weathers readily to limonite and is, therefore, rare in clays. It is magnetic.

Hematite is quite common in some clays, functioning as a flux. Like all forms of iron oxide, it produces a reddish color in fired ware.

Chert (SiO_2). Silica formed in the weathering process occurs in clay in an amorphous condition. Chert is one of these forms. Its properties are similar to quartz, but it is non-crystalline and changes to tridymite and cristobalite at lower temperatures than quartz.

Limonite is a yellowish-brown material very common in low-grade clays. It occurs in clays as concretions, rusty-looking grains, or as a film of fine grains on the surfaces of other grains. Under the last conditions, a small amount suffices to impart a dark color to the clay. It is amorphous in structure, and functions as a plastic and a flux. It is the usual end-product in the weathering of the iron oxides of the igneous rocks. It is the most stable form of iron insofar as weathering is concerned.

Siderite. When iron compounds weather in the presence of water containing carbon dioxide, siderite may form. It is an iron carbonate and occurs as concretions, stringers of coarse grains, or as films of fine grains on other material. It is crystalline in structure. It is usually brown or nearly black in color. It alters readily to limonite and so is not very common in clay.

Pyrite. This is one of the most common and most troublesome impurities in some clays. Clays containing pyrite must be fired carefully so that the pyrite will be completely oxidized and the sulfur expelled, otherwise bloating and scumming may result in the fired ware. Localized discolorations also develop. Pyrite is formed when weathering takes place in the presence of sulfur compounds or from the reduction of sulfates by carbon. It is crystalline, yellowish in color, brittle, and metallic in lustre. It functions as a flux.

Calcite. This is a white crystalline material which is quite common in clays. It occurs as concretions and as grains finely disseminated through the clay. It decomposes under fire, giving off its CO_2 at a temperature near the vitrifying temperature of most ware and can, therefore, cause bloating. It functions as a flux. Sometimes it is added under the name of whiting to clay bodies for its fluxing effect. It is formed from lime compounds in igneous rocks by weathering under conditions where carbon dioxide is present in excess.

Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is a crystalline material quite common in some clays. It occurs as fine grains or crystalline plates. The water is eliminated at a very low temperature and the sulfur at a high temperature. Gypsum is likely to cause bloating and scumming in fired ware. It functions as a flux. It may form from lime in igneous rock under conditions where sulfur compounds are present.

Magnesite. This is a crystalline material not common in clays. It forms from the magnesium compounds of igneous rock under conditions where carbon dioxide is present in excess. It decomposes at a moderately high temperature, giving off carbon dioxide.

Dolomite is a crystalline material not too common in clays. Its properties are in general intermediate between calcite and magnesite.

Carbonaceous material. Lignite, peat, and other forms of carbon may occur in clays. Some shales contain as much as 10 percent. Some carbon is present in most clays. It adds somewhat to the plasticity of the clay, but has no definite function. Its presence is always objectionable and if not carefully burned off when the clay is fired, it will cause bloating and black coring.

The mineral composition of a clay may be obtained by a number of different methods. Often for very accurate results it is necessary to use two or more methods. Chemical analyses have been and must always remain the first and most essential step in the study of the mineral composition of clays. However, analyses together with all other mineralogical studies must start with assurance of essential purity.

The petrographic microscope is one of the most useful instruments for determining the minerals present in any clay. A sample of clay is ground to pass a 200-mesh screen. Fine grinding breaks down the grain aggregates into individual mineral grains. A few grains of this fine powder, immersed in an oil of selected index of refraction, can be examined under the microscope, and the various minerals are identified by their optical properties.

The differential thermal analysis method for identification of the clay minerals utilizes the differences in reactions exhibited by clay minerals during heat treatment. A sample is heated at a constant rate and a record is made of any exothermic or endothermic reactions. Each mineral has a characteristic temperature at which these reactions occur and the extent of the reaction is different for different minerals. Thus individual minerals may be identified by the pattern of the plotted results.

The application of X-ray methods to the study of crystalline materials has been used, with a high degree of success, in the identification of clay minerals. The lack of any external form, the exceeding fineness of grain, and the wide variation in composition in most clay minerals present problems which have been solved only by X-ray methods.

The electron microscope has some inherent limitations as an instrument for investigation of mineral composition; the very fine grain size and ready dispersability of clay minerals gives it a usefulness in their study, and it has contributed some pertinent information about some of the clay minerals.

Color reactions have been found helpful in identifying clay materials. A number of organic compounds undergo a reaction which gives a color change in the presence of certain clay minerals. Certain precautions must be observed in applying this technique which has been used in clay prospecting and in evaluation of different beds in a clay pit.

A method of determining the approximate mineral composition is by rational analysis. In this procedure, the minerals are separated from one another by chemical solution, the relative amounts of each being indicated by the amount of material remaining undissolved and the amount going into solution. The procedure is as follows: the sample, consisting of 2 grams, is digested 6 to 8 hours with 20 cc. of dilute H_2SO_4 and then evaporated to dryness. Add 1 cc. of conc. HCl and an excess of boiling water. Filter the insoluble residue and wash. Digest the residue with 15 cc. of 10 percent $NaOH$ solution. Dilute with water, filter and wash first with water and then with dilute HCl . The residue is ignited and weighed. The residue is calculated as quartz and feldspar. The difference between the weight of the original sample and the residue is the weight of clay substance. It went into solution. So, also, did calcite and some other minerals.

The residue is analyzed for Al_2O_3 . The weight of alumina obtained is multiplied by 5.41, which gives the weight of feldspar. Subtracting

this from the weight of the residue gives the weight of quartz. The percentages of each may be obtained by dividing the weight of the sample into the weight of each constituent and multiplying by 100. The results may be expressed in terms of plastic, flux, and filler.

The method is not scientifically accurate, but it yields information regarding the approximate mineral composition and how the clay will behave on the basis of the ratio of filler, flux, and plastic. It is most useful for clays that consist essentially of quartz, feldspar, and hydrous aluminum silicate. Iron compounds and lime compounds go into solution with the clay substance, making the figure for it too high. Other soluble substances do the same thing. Other sources of error are as follows:

1. Some clays are not entirely decomposed by H_2SO_4 .
2. Fine-grained feldspar may dissolve in H_2SO_4 to the extent of about 2 1/4 percent, and fine-grained mica may dissolve to a slight extent.
3. Not all the silica from the decomposition of the hydrous aluminum silicates may dissolve in the caustic soda.

Complete chemical analysis and mineralogical analysis give much more accurate results than rational analysis. Rational analysis is useful, however, in determining the variation of a clay from point to point in its bed.

Chapter 4

CHEMICAL COMPOSITION OF CLAYS

Unlike the mineralogical analysis, which gives composition in terms of minerals, the ultimate chemical analysis gives composition in terms of the oxide constituents. In some cases these oxide constituents are combined to form the minerals, and in other cases are free. The total content of the basic elements is determined and the results are calculated in terms of the oxides. Thus the total amount of calcium is determined and then it is calculated and expressed as calcium oxide, although there is no free calcium oxide in the clay. In order for the chemical composition to become really significant, it must be interpreted in terms of the minerals represented. For this reason, conversion of the chemical analysis into mineralogical analysis is desirable. We know that K_2O indicates feldspar, and that a rather definite amount of feldspar is represented by each per cent of K_2O . Feldspar represents a fluxing effect, and consequently K_2O does. It is frequent practice, therefore, to interpret fluxing effect directly from the content of K_2O without going to the trouble of converting it into per cent of feldspar. However, interpreting a chemical analysis in terms of minerals requires an understanding of the subject.

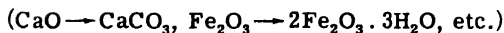
In order to change an ultimate chemical analysis into a mineralogical analysis, one must have a knowledge of how the chemicals are distributed among the minerals. In the case of impure clays, it is difficult to make the conversion without at least a partial mineralogical analysis, but in the case of high-grade clays it can be done with fair accuracy, although certain assumptions have to be made that are not always strictly accurate. It is assumed that the free silica is that portion of the total silica content which is not in the feldspar and kaolinite. If some calcium silicate is present, that assumption is wrong. However, in most cases, the assumption holds, and the result obtained in calculating the minerals has a fair degree of accuracy.

Most minerals found in clays may be looked upon as a chemical combination of various oxides. This is illustrated in the following table:

<u>Oxide</u>	<u>Minerals involved</u>
SiO ₂	Feld., micas, amph., pyrox., quartz, hy. -al. silicates, silica.
Al ₂ O ₃	Feld., hy. -al. silicates, micas, amph., pyrox., aluminum oxide and hydrates.
Fe ₂ O ₃	Limonite, hematite, magnetite.
FeO	Pyrite, siderite, amph., pyrox., magnetite, biotite, ilmenite.
CaO	Gypsum, fluorite, amph., pyrox., calcite, dolomite, feldspar.
MgO	Dolomite, magnesite, amph., pyrox., serpentine.
K ₂ O	Feldspar, mica.
Na ₂ O	Feldspar, mica.
TiO ₂	Rutile, ilmenite.
SO ₃	Gypsum, pyrite.
CO ₂	Calcite, magnesite, dolomite, organic material.
H ₂ O	Hy. -al. silicates, mica, limonite, gypsum.

Transferring chemical analysis to mineralogical analysis involves the following assumptions:

1. Assume all the alkalis are present as K₂O in microcline.
2. Assume that the K₂O is combined with the necessary part of the total Al₂O₃ and SiO₂ to form the microcline.
3. Assume the remaining Al₂O₃ is all combined with a portion of the remaining silica and water to form kaolinite.
4. Assume that the remaining silica is free quartz.
5. Assume the remaining oxides are combined with other oxides to make up the most commonly occurring minerals of these oxides.



These assumptions are expressed in the form of equations as follows:

- a. Microcline = % (K₂O + Na₂O) x 5.9
- b. % Al₂O₃ in microcline = 18.3% of total microcline.
- c. % SiO₂ in microcline = 64.7 % of total microcline.
- d. % Al₂O₃ in kaolinite = total % Al₂O₃ - % Al₂O₃ in microcline
- e. % kaolinite = % Al₂O₃ in kaolinite x 2.53

f. SiO_2 in kaolinite = 46.5% of total kaolinite

g. Free quartz = total % SiO_2 - (SiO_2 in microcline + SiO_2 in kaolinite)

The factors used in (a) and (e) are obtained from the formula weights of microcline and kaolinite. The molecular formula for microcline is $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$. Molecular weights are $\text{K}_2\text{O} = 94$, $\text{Al}_2\text{O}_3 = 102$, $\text{SiO}_2 = 60$. Therefore, $\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 = 556$ and the factor to convert K_2O to microcline would be $\frac{556}{94} = 5.9$.

Similarly, kaolinite is $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$, and $\text{Al}_2\text{O}_3 = 102$, $\text{SiO}_2 = 60$, $\text{H}_2\text{O} = 18$. Therefore, $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O} = 258$ and the factor to convert Al_2O_3 to kaolinite would be $\frac{258}{102} = 2.53$.

The percent factors used in (b), (c), and (f) are obtained thus:

$\text{K}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 = 556$; per cent Al_2O_3 in microcline = $\frac{102}{556} \times 100$
18.3 % and SiO_2 in microcline = $\frac{360}{556} \times 100 = 64.7\%$.

A kaolin has the following ultimate chemical analysis:

SiO_2	57.08%
Al_2O_3	29.94%
Fe_2O_3	0.85%
K_2O	2.26%
H_2O	9.87%
	<hr/>
	100.00%

Calculate its mineralogical analysis.

- % microcline = $2.26 \times 5.9 = 13.33\%$
- % Al_2O_3 in microcline = 18.3% of $13.33 = 2.44\%$
- % SiO_2 in microcline = 64.7% of $13.33 = 8.62\%$
- % Al_2O_3 in kaolinite = $29.94 - 2.44 = 27.50\%$
- % kaolinite = $27.50 \times 2.53 = 69.58\%$
- % SiO_2 in kaolinite = $69.58 \times \frac{46.5}{100} = 32.35\%$
- Free quartz = $57.08 - (8.62 + 32.35) = 16.11\%$
- Total composition --

microcline	13.33%	-- flux
kaolinite	69.58%	-- plastic
quartz	16.11%	-- filler

The remaining 1 % may be accounted for as limonite. It is evident that this clay can be quite plastic, if the kaolinite has the proper physical properties; that it will have a moderate drying shrinkage, on account of containing a moderate amount of free quartz; and that it will have a rather high fusibility, on account of the rather low content of flux.

The calculation of the ultimate chemical analysis from the mineral composition is also possible. Assume that a clay is made up of 70 % kaolinite, 10 % microcline, and 20 % quartz. The 70 % of kaolinite

would contain

$$\frac{102}{258} \times .70 = 27.5\% \text{ Al}_2\text{O}_3$$

$$\frac{120}{258} \times .70 = 32.4\% \text{ SiO}_2$$

$$\frac{36}{258} \times .70 = 9.7\% \text{ H}_2\text{O}$$

The 10 % of microcline would contain

$$\frac{94}{556} \times .10 = 1.7\% \text{ K}_2\text{O}$$

$$\frac{102}{556} \times .10 = 1.8\% \text{ Al}_2\text{O}_3$$

$$\frac{360}{556} \times .10 = 6.5\% \text{ SiO}_2$$

The 20% of quartz would contain

$$\frac{60}{60} \times .20 = 20\% \text{ SiO}_2$$

$$\text{Total SiO}_2 = 32.4 + 6.5 + 20.0 = 58.9\%$$

$$\text{Total Al}_2\text{O}_3 = 27.5 + 1.8 = 29.3\%$$

$$\text{Total K}_2\text{O} = 1.7\%$$

$$\text{Total H}_2\text{O} = 9.7\%$$

$$99.6\%$$

It becomes customary, with experience, to draw conclusions directly from the chemical analysis without calculating the mineral compositions. We see that the microcline content is about 6 times the alkali content. If a clay contains as much as 5 percent alkali, it would have a low fusion point. Similarly, other conclusions are drawn directly from the chemical composition as follows:

- a. SO_3 indicates gypsum or pyrite. In either case, the danger of scumming or bloating is present. Care in firing is required.
- b. CO_2 indicates carbonates or organic matter. In either case, if the CO_2 is present in large amount, bloating is a possibility, and care must be exercised in firing.
- c. TiO_2 reduces the refractoriness slightly and develops a straw color.
- d. H_2O indicates the amount of kaolinite, and has a bearing upon the amount of shrinkage to be expected.
- e. SiO_2 in large excess indicates much free quartz with low workability and low shrinkage.
- f. Fe_2O_3 results in coloration and low fusibility. If present in less than 1 percent the color will be white. If present in amounts between 2 percent and 3 percent the color will be buff. If present in larger amounts, the color will be some shade of red. Lime tends to bleach the red color.

CHEMICAL NOTATION AND CONSTITUTION OF CERAMIC MATERIALS

The constitution of chemicals such as salt is, in chemistry, conceived as being made up of two radicals or ions; a basic radical with a positive charge and an acid radical with a negative charge. In water, salts dissociate electrolytically into these two radicals. For example, sodium nitrate dissociates into the basic radical Na and the negative radical NO_3 , thus: $\text{NaNO}_3 \rightleftharpoons \text{Na}^+ + \text{NO}_3^-$. With the removal of the dissociating medium, the attraction of the oppositely-charged radicals causes them to unite to constitute the salt. For this reason, sodium nitrate is thought of as being made up of Na and NO_3 . In water-solution chemistry, this is a very useful conception. The theory of chemical reactions is based upon it. It applies definitely when soluble substances are involved. In the case of insoluble substances, however, there can be no electrolytic dissociation and there is no actual formation of ions. This is the case with practically all ceramic materials. They are insoluble. For this reason, some other conception of the constitution of ceramic materials is desirable.

Calcium carbonate (CaCO_3) would, if it were soluble, dissociate into a positive calcium ion and a negative CO_3 ion, but it is insoluble. It is better to conceive of it as being composed of the oxide CaO and the oxide CO_2 . To show this constitution, use is made of the molecular formula instead of the ionic formula, and calcium carbonate is written $\text{CaO} \cdot \text{CO}_2$, instead of CaCO_3 . This concept of ceramic materials being made up of oxides instead of ions helps in understanding their behavior when heated. When calcite is heated, it breaks down into CaO and CO_2 , not Ca and CO_3 . Molecular instead of ionic formulas are the rule in ceramics. Kaolinite is usually written $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$, and not $\text{Al}_2\text{Si}_2\text{O}_7 \cdot 2\text{H}_2\text{O}$ or $\text{H}_4\text{Al}_2\text{Si}_2\text{O}_9$.

The ionic conception of ceramic materials, however, is useful in understanding their behavior under some conditions. Kaolinite is not a hydrated salt as its molecular formula might indicate. It is an exceedingly weak acid with an ionic formula $\text{H}_4\text{Al}_2\text{Si}_2\text{O}_9$. Although it is not soluble and does not ionize, it may be conceived of as an acid like H_2CO_3 or H_2SO_4 or any other acid. The hydrogen may be replaced by a basic element with the formation of a salt, as in any neutralization reaction. By replacing the H_4 with Ca, we have anorthite, $\text{CaAl}_2\text{Si}_2\text{O}_8$, or, written molecularly, $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$. The theory is that kaolinite is not a salt but an aluminosilicic acid. It is called a

"di" silicic acid because there are two molecules of silica to one of alumina. The alumino-silicic acids are listed below: *

Alumino-mono-silicic acid	$H_2Al_2SiO_6$	or	$Al_2O_3 \cdot SiO_2 \cdot H_2O$
Alumino-di-silicic acid	$H_4Al_2Si_2O_9$	or	$Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$
Alumino-tri-silicic acid	$H_6Al_2Si_3O_{13}$	or	$Al_2O_3 \cdot 3SiO_2 \cdot 4H_2O$
Alumino-tetra-silicic acid	$H_8Al_2Si_4O_{17}$	or	$Al_2O_3 \cdot 4SiO_2 \cdot H_2O$
Alumino-penta-silicic acid	$H_{10}Al_2Si_5O_{21}$	or	$Al_2O_3 \cdot 5SiO_2 \cdot H_2O$
Alumino-hexa-silicic acid	$H_{12}Al_2Si_6O_{25}$	or	$Al_2O_3 \cdot 6SiO_2 \cdot H_2O$

The salts of these acids are as follows:

Alumino-mono-silicate	$MgO \cdot Al_2O_3 \cdot SiO_2$	Augite
Alumino-di-silicate	$CaO \cdot Al_2O_3 \cdot 2SiO_2$	Anorthite
Alumino-tetra-silicate	$K_2O \cdot Al_2O_3 \cdot 4SiO_2$	Leucite
Alumino-hexa-silicate	$K_2O \cdot Al_2O_3 \cdot 6SiO_2$	Microcline

These are the only acids and salts of the series.

The weathering of feldspar is merely the conversion of the "salt", feldspar, back into the alumino-hexa-silicic acid $Al_2O_3 \cdot 6SiO_2 \cdot H_2O$. When a clay refractory brick is acted upon by a basic slag at high temperature, the acid is converted to the salt and the refractory brick breaks down.

Molecular formulas are useful in expressing the composition of ceramic mixtures as well as compounds. This practice is not strictly accurate, but is very useful and is commonly employed. By using coefficients with the various oxides, the composition of a mixture can be expressed.

The following is the molecular formula of a glaze:

$$\begin{array}{rcl}
 .81 & CaO &) \\
 .06 & K_2O &) \quad .09 \, Al_2O_3 \quad 4.6 \, SiO_2 \\
 \hline
 .13 & Na_2O &) \\
 \hline
 1.00 & &
 \end{array}$$

It shows that the various oxides are present in relative amounts represented by the products of the various coefficients times their respective molecular weights. The practice is to write the basic oxides first, the amphoteric oxides next, and the acid oxides last. The order is RO R_2O_3 RO_2 . In any molecular formula, the sum of the coefficients of the RO group must, conventionally, total 1.00.

The procedure for calculating the percentage or batch composition from the molecular formula is as follows:

1. Multiply the molecular weight of each oxide by its coefficient.
2. Obtain the sum of these products.

3. Divide the sum into each of the products and multiply by 100.

Example:

$$\begin{array}{r}
 .81 \text{ CaO} \quad) \\
 .06 \text{ K}_2\text{O} \quad) \quad .09 \text{ Al}_2\text{O}_3 \quad 4.6 \text{ SiO}_2 \\
 .13 \text{ Na}_2\text{O} \quad) \\
 \hline
 .81 \times 56 = 45.36 \text{ (CaO)} \quad - - - - \frac{45.36}{344.24} \times 100 = 13.2\% \text{ CaO} \\
 .06 \times 94 = 5.64 \text{ (K}_2\text{O)} \quad - - - - \frac{5.64}{344.24} \times 100 = 1.6\% \text{ K}_2\text{O} \\
 .13 \times 62 = 8.06 \text{ (Na}_2\text{O)} \quad - - - - \frac{8.06}{344.24} \times 100 = 2.3\% \text{ Na}_2\text{O} \\
 .09 \times 102 = 9.18 \text{ (Al}_2\text{O}_3) \quad - - - - \frac{9.18}{344.24} \times 100 = 2.7\% \text{ Al}_2\text{O}_3 \\
 4.6 \times 60 = 276.00 \text{ (SiO}_2) \quad - - - - \frac{276}{344.24} \times 100 = 80.2\% \text{ SiO}_2 \\
 \hline
 344.24 \qquad \qquad \qquad 100.0\%
 \end{array}$$

The calculation of the molecular formula from the composition is done as follows:

- Ascertain the total percentage of each constituent from the analysis.
- Divide the total amount of each constituent by its molecular weight.
- Write the oxides in the order RO R₂O₃ RO₂ and write as coefficients of these oxides the quotients, obtained in (b).
- Divide the coefficients by the sum of RO coefficients.

Example: Find the molecular formula of a body which has the following analysis:

$$\begin{array}{l}
 \text{SiO}_2 - 49\% \\
 \text{Al}_2\text{O}_3 - 36\% \\
 \text{K}_2\text{O} - 2\% \\
 \text{CaO} - 1\% \\
 \text{H}_2\text{O} - 12\%
 \end{array}$$

Solution:

$$\begin{array}{l}
 \text{SiO}_2 = 49 \div 60 = .817 \\
 \text{Al}_2\text{O}_3 = 36 \div 102 = .353 \\
 \text{K}_2\text{O} = 2 \div 94 = .021 \\
 \text{CaO} = 1 \div 56 = .018 \\
 \text{H}_2\text{O} = 12 \div 18 = .667
 \end{array}$$

$$\begin{array}{r}
 .018 \text{ CaO} \\
 .021 \text{ K}_2\text{O} \\
 \hline
 .039
 \end{array}
 \begin{array}{l}
) .353 \text{ Al}_2\text{O}_3 \quad .817 \text{ SiO}_2 \quad .667 \text{ H}_2\text{O}
 \end{array}$$

Divide by .039

$$\begin{array}{r}
 .46 \text{ CaO} \\
 .54 \text{ K}_2\text{O} \\
 \hline
 1.00
 \end{array}
 \begin{array}{l}
) 9.05 \text{ Al}_2\text{O}_3 \quad 20.95 \text{ SiO}_2 \quad 17.2 \text{ H}_2\text{O}
 \end{array}$$

The calculation of the molecular formula from the analysis of the individual ingredients is done in the same way, but is a little more complicated.

Example: Calculate the molecular formula of a glaze composed of 34% Cornwall stone, 34% feldspar, 22% whiting, and 10% flint, the chemical compositions of which are as follows:

	<u>K₂O</u>	<u>Na₂O</u>	<u>CaO</u>	<u>Al₂O₃</u>	<u>SiO₂</u>	<u>Other Constituents</u>
Cornwall stone	5.7	3.0	1.29	16.6	70.4	3.0
Feldspar	11.1	2.2	0.29	18.5	65.7	1.5
Whiting	-	-	56.00	-	-	44.0
Flint	-	-	-	-	98.4	1.6

Procedure:

- a. Ascertain the total percent of each constituent from the chemical analysis.

	<u>K₂O</u>	<u>Na₂O</u>	<u>CaO</u>	<u>Al₂O₃</u>	<u>SiO₂</u>	<u>Other Constituents</u>
Cornwall stone	1.94	1.02	0.44	5.64	23.94	1.02
Feldspar	3.78	0.75	0.10	6.49	23.37	0.51
Whiting	-	-	12.32	-	-	9.68
Flint	-	-	-	-	9.84	0.16
	<u>5.72</u>	<u>1.77</u>	<u>12.86</u>	<u>12.13</u>	<u>57.15</u>	<u>11.37</u>

- b. Divide the total per cent of each constituent by its molecular weight.

$$\begin{array}{lcl}
 \text{K}_2\text{O} & - & 5.72 \div 94 = .061 \\
 \text{Na}_2\text{O} & - & 1.77 \div 62 = .029 \\
 \text{CaO} & - & 12.86 \div 56 = .230 \\
 \text{Al}_2\text{O}_3 & - & 12.13 \div 102 = .119 \\
 \text{SiO}_2 & - & 57.15 \div 60 = .952
 \end{array}$$

- c. Write the oxides in the order RO R₂O₃ RO₂ with the quotients obtained above as their coefficients.

$$\begin{array}{rcl}
 .061 & \text{K}_2\text{O} &) \\
 .029 & \text{Na}_2\text{O} &) \\
 .230 & \text{CaO} &) \\
 \hline
 .320 & &
 \end{array}
 \quad
 \begin{array}{rcl}
 .119 & \text{Al}_2\text{O}_3 & \\
 .952 & \text{SiO}_2 &
 \end{array}$$

- d. Divide the coefficients by the sum of the RO coefficients.

$$\begin{array}{rcl}
 .19 & \text{K}_2\text{O} &) \\
 .09 & \text{Na}_2\text{O} &) \\
 .72 & \text{CaO} &) \\
 \hline
 1.00 & &
 \end{array}
 \quad
 \begin{array}{rcl}
 0.37 & \text{Al}_2\text{O}_3 & \\
 2.97 & \text{SiO}_2 &
 \end{array}$$

Example: Calculate the mixture of the raw ingredients, assuming them to be pure, of the following glaze:

.17 K₂O)
 .43 CaO)
 .32 ZnO) .46 Al₂O₃ 3.31 SiO₂ + 2% Soda Ash
 .08 PbO)

Solution

Equivalents of raw materials required	Equivalents of Glaze Formula					
43 CaCO ₃	17 K ₂ O	43 CaO	32 ZnO	08 PbO	46 Al ₂ O ₃	3.31 SiO ₂
		43 CaO				
Difference	17 K ₂ O	-	32 ZnO	08 PbO	46 Al ₂ O ₃	3.31 SiO ₂
32 ZnO			32 ZnO			
Difference	17 K ₂ O	-	-	08 PbO	46 Al ₂ O ₃	3.31 SiO ₂
08 White lead				08 PbO		
Difference	17 K ₂ O	-	-	-	46 Al ₂ O ₃	3.31 SiO ₂
17 Feldspar	17 K ₂ O				17 Al ₂ O ₃	1.02 SiO ₂
Difference	-	-	-	-	29 Al ₂ O ₃	2.29 SiO ₂
29 Kaolin					29 Al ₂ O ₃	58 SiO ₂
Difference	-	-	-	-	-	1.71 SiO ₂
1.71 Flint						1.71 SiO ₂

Therefore we have

	Equivalents		Equivalent Weight		
CaCO ₃	.43	x	100	=	43.00
ZnO	.32	x	81	=	25.92
2PbCO ₃ . Pb(OH) ₂	.08	x	258.5	=	20.68
Feldspar	.17	x	556	=	94.52
Kaolin	.29	x	258	=	74.82
Flint	1.71	x	60	=	102.60
					<u>361.54</u>
Soda Ash	-	361.54 x .02 =			7.23
			Total Batch	=	<u>368.77</u>

All matter is made up of molecules, molecules in turn are composed of atoms, and atoms consist of electrons, protons, and neutrons. Electrons are negative charges of electricity. Atoms of different elements differ only in the number and arrangement of electrons.

Aggregates of matter may exist in the gaseous, liquid or solid states. The ceramist is concerned with matter in the solid state primarily and in the liquid state secondarily. The gaseous state of

matter is of little importance in ceramics. Between the liquid and the solid states lie the slip and paste condition of matter, each of which is of great importance to ceramics. Solid matter may exist in either the colloidal or non-colloidal condition, and in either the crystalline or amorphous condition.

In the crystalline state, matter has definite geometric form. Amorphous matter has no definite form or systematic arrangement of the atoms. Crystalline matter is usually denser, harder, and more inert chemically than amorphous matter. In the firing of ceramic ware, it is usually desirable to convert as much matter as possible into the crystalline state. It is more stable in that condition. The amorphous state of matter is that in which there is no definite form and no definite alignment of atoms. Glass is matter in firm state without definite form. The glassy state of matter is one of the important bonds that develop in fired ware.

Amorphous matter may be cellular like lava. In this case, voids or pockets occur in the matter in large amounts. This is a condition of matter required for insulating purposes. Porosities as high as 80 to 90 percent are desirable as insulating products.

The paste condition of matter is a mixture of liquid and solid, the solid predominating. If clay and water are mixed in such proportion as to get a mixture that does not flow except by applied pressure, the mixture is a paste. Slips are mixtures of liquids and solids, the liquids predominating. They flow like water, but are restrained more or less by their viscosity.

The colloidal state. In 1861, Graham observed that certain substances like glue would not diffuse through a semi-permeable membrane, whereas substances like salt in solution would. He conceived of two classes of substances, one of which would not diffuse through these membranes and the other which would. He called the substance of the first class "colloids" from "Kolla" meaning gum. It has since been found that Graham's understanding of the matter was wrong. We now know that any kind of matter may be in either the colloidal or non-colloidal condition, depending entirely upon the size of the particles. When particles of solid matter are smaller than .0001 mm. in diameter, they are in the colloidal condition. To render any matter colloidal, it is only necessary to reduce the particle size to less than .0001 mm. This cannot always be done by grinding. Some dispersion medium is usually necessary. When clay is slaked in water, some of it becomes colloidal in size and the water is the dispersion medium. When an electric arc is made between gold electrodes under water, particles of gold are torn from the electrode in colloidal size and the water soon takes on a beautiful purple color. It has the appearance of a true solution, but instead it is a suspension of solid gold particles in water. Thus we have suspensions of colloids contrasted with solutions of soluble substances. Unlike solutions, the freezing and boiling point of the suspension is the same as that of the dispersion medium.

Material in colloidal suspension is in the "disperse" phase. Materials in this colloidal condition possess remarkable properties. Each particle is charged with electricity. Some matter takes on a positive charge; some a negative charge. All particles of one substance, being charged the same, repel each other, and are therefore constantly moving about in all directions in the dispersion medium. Under the microscope, this movement is displayed as a magnificent play of colors and is known as the Brownian movement. Because they are charged alike and constantly repelling one another, the particles remain in suspension indefinitely. Non-colloidal matter, on the other hand, settles out rapidly. If platinum electrodes are placed in a suspension of dispersed colloids and a direct current is passed through it, the colloidal particles will accumulate on the electrode of the sign opposite to that of the charged colloidal particles. This is known as "kataphoresis".

If the charge on dispersed colloidal particles is neutralized, the particles will gather together into aggregates or flocs. Flocculation of the dispersed colloidal particles may be accomplished by introducing another colloid of opposite sign, or by adding a solution of an electrolyte having a strongly charged ion of opposite sign. Thus, colloidal iron hydroxide, which is positively charged, will flocculate a suspension of clay by neutralizing its negative charge. So will hydrochloric or other strong acid. The hydrogen ion of the acid is strongly charged positively. Colloidal material in the flocculated or coagulated condition is called a colloidal "gel". In the dispersed condition it is called a "sol". If water is the dispersion medium, they are called "hydrogels" and "hydrosols" respectively. This reaction from sol to gel is reversible. Anything that restores the charge to the gel colloids changes it back to the sol condition. These facts are very important in ceramics, as they affect castability, plasticity, and many other working properties of clays.

In colloidal gels, the particles are arranged in a mesh or network which enables them to hold large amounts of the dispersion medium. Gels of iron hydroxide can be made which consist of as much as 90 percent water, yet the mass is of a jelly-like consistency. Advantage is taken of this tremendous adsorption capacity commercially. Bentonite is used for absorbing impurities from oils, silica gel for absorbing gasoline, alcohol, or benzine. The tremendous surface exposed is the key to this absorption capacity. This is brought out by the following data:

<u>Length of Edge</u>	<u>Number of Cubes</u>	<u>Total Surface</u>
1 cm. (0.3937 in.)	1	6 sq. cm. (0.93 sq. in.)
1 mm. (.0394 in.)	1,000	60 sq. cm. (9.3 sq. in.)
.01 mm. (.0004 in.)	1,000,000,000	6000 sq. cm. (930 sq. in.)
.0001 mm.	1,000,000,000,000,000	60 sq. m. (645 sq. ft.)
.01 mm.	10^{27}	(148 acres)

Diameters

10 mm.	= 2 mesh	
0.147 mm.	= 100 mesh	Screening
.074 mm.	= 200 mesh	
.001 mm.	= 1 micron or μ	Settling
.0001 mm.	= 0.1 micron	
.000,001 mm.	= 1 milli micron or $m \mu$	Colloid
.000,000,001 mm.	= .001 $m \mu$	True Solution

Colloids are hygroscopic when dried. They adsorb liquids or gases or solids. Bentonite is a colloidal material which, when dried, will adsorb enough water to increase its bulk 13 times. Such materials are characterized by large expansion on adsorption and high shrinkage on drying.

PHYSICAL PROPERTIES OF CLAY

The physical properties of any clay are very important in determining its use as an industrial material. The physical properties will determine, to a large extent, the type of product that can be made from the clay, the method of forming that will be used, and the kind of machinery that will be needed to manufacture ceramic articles.

Plasticity is one of the most important properties of clays. Some clays possess this property in a remarkable degree. Clays differ in their capacity to develop plasticity, and this capacity can be increased or decreased to a large degree by different kinds of treatment. The behavior of clays in the forming operation is determined largely by the degree of plasticity that has been developed in them.

Plasticity is defined as that property of matter which enables it to be deformed or changed into any shape, retaining that shape when the deforming force is removed. A clay paste possesses this property. So do lime putty and a few other substances. Plasticity differs from viscosity in that a viscous substance can be deformed into any shape but will not retain the deformed shape when the deforming force is removed. A viscous substance continues to deform under gravity. An elastic substance returns to the original form when the deforming force is removed.

Seeger defines plasticity as that property which solid substances have of absorbing and holding liquids in their pores, and forming a mass that can be pressed or kneaded into any shape, which it retains when the pressure ceases; and which, on the withdrawal of the liquid, changes to a hard mass.

Theories have been advanced from time to time to explain the plasticity of clays. All of them are worth study because they represent certain properties of clays which are important.

1. The combined-water theory is one of the early ones advanced to explain the plasticity of clays. According to this theory, the plasticity of clays is due to hydrated substances, particularly hydrous aluminum silicates. This theory is based on the facts that: (a) all clays are plastic in greater or less degree and all contain hydrated substances, and (b) driving off the water of hydration destroys the plasticity. These arguments are not conclusive, because the degree of plasticity is not proportional to the degree of hydration. A ball clay may be more plastic than a kaolin, yet the latter may contain a larger percentage of water of hydration. Furthermore, dehydration

does not necessarily destroy all plasticity. It is evident that this theory does not get to the root of the matter.

2. The molecular-attraction theory was next advanced as an explanation for clay plasticity. This has to do, not with the combined water, but with the uncombined water. It is assumed that clay grains have an attraction for water whereby they become coated with an envelope of water which forms a film on their surfaces, thereby lubricating the grains. This lubrication permits them to slide easily over each other, thereby making the paste plastic and workable. This theory assumes that the clay molecules have particular properties which give them this unusual power. Clays are supposed to differ in degree in their constitution and therefore the thickness of the adsorbed film varies with the resultant difference in the degree of plasticity exhibited by different clays. When the film is broken by removing the water, the grains come into contact and the lubrication effect is lost. There is much of merit in this theory, but it is vague.
3. The fineness-of-grain theory was next proposed. The two foregoing theories were based on the water content. This one is based on the solid phase or grains of the clay. It is assumed that clay in water disintegrates into grains of smaller size than most other substances. The small size of the grains is supposed to account for plasticity. It should be noted that the colloid concept was not available at this time. If the clay grains differ from grains of ordinary non-plastic material only in that they are finer, it seemed logical to deduce that any material may be made plastic by fine grinding. When such materials as quartz or mica are ground as fine as possible, only a little plasticity is developed. This indicates that there must be something about clays which is different from ordinary materials and which should be included in the plasticity theory.
4. The plate theory was next advanced. This theory is based on the shape of the grains. It is suggested that when clay grains are in the form of plates, very small and not bunched, the clay is of relatively high plasticity. Microscopic examination of many clays revealed this plate structure. In some clays they were large, .003 to .001 inch; in others they were extremely small. Some were bunched and some isolated. Those having small plates and not bunches were the more plastic. This led to speculation as to means of modifying the plasticity of clays. Ageing, which might tend to break down the bunched bundles, improves plasticity. However, this theory, as all others, does not satisfy one in quest of the real explanation of plasticity.
5. The interlocking grain theory has the advantage over the others in explaining the dried strength of clays, a property which usually roughly parallels plasticity. It is assumed that what accounts for one of these two properties could easily account for the other. It is assumed that clay grains are of such a character that they interlock. This can easily explain strength, but is not very convincing in explaining plasticity. However, there is a connection between strength and plasticity that remains to be explained in some other way.

6. The colloidal theory of plasticity adequately explains the plasticity of clays by assuming that some hydrous aluminum silicates or other minerals are present as colloidal sols and gels. It is further assumed that the grains of the clay are surrounded by an envelope of water and this colloidal material. The result is lubrication in the paste condition and strength in the dry condition. Lubrication is attained by virtue of the like-charged colloidal particles repelling one another, and dry strength occurs when the dispersion medium (water) is withdrawn and the colloidal particles adhere together.

Ample evidence is available to prove that colloidal matter does exist in clays, and that it varies in amount with different clays. According to this theory it should be possible to increase or decrease the plasticity of a clay by the addition of a flocculant or an electrolyte. Precipitation or flocculation of the clay sol can be brought about by introducing acids or acid salts. The order of effectiveness of coagulants is as follows: HCl —30, HNO_3 —28, H_2SO_4 —20, CaCl_2 —15, $\text{Ca}(\text{NO}_3)_2$ —10, CaSO_4 —5, KCl —3, NaCl —1.

Clay in the gel condition has relatively high plasticity and viscosity. Clay in the sol condition has relatively high fluidity. When clay is used in the paste condition, it is usually preferable to have the clay in a gel condition, unless it develops too much plasticity. When clay is used in a slip condition, particularly for casting, it is usually preferable to have it in the sol condition.

Deflocculation is the reverse of flocculation. It is effected by treatment with a base or substance yielding the strong hydroxyl ion. Sodium silicate and sodium carbonate are usually preferred for this purpose with clays. They hydrolyze, yielding the hydroxyl ion. For maximum deflocculation, a definite and very small amount of these salts is required.

Clay in the gel condition renders clay pastes low in miscibility. It requires much kneading to mix thoroughly two clay pastes. It is better to mix the materials dry or in the slip condition, and then adjust the mixture to the paste consistency. Altering the plasticity of clays has industrial applications. Sometimes the plasticity must be reduced and sometimes increased. Different clays vary greatly in the amount of water required for maximum plasticity. The water for plasticity will vary anywhere from 10 % to 40 %. Methods of increasing the plasticity of a clay paste include the following:

- a. By the addition or removal of a suitable amount of water.
- b. By more thorough incorporation of the water; pugging and ageing.
- c. By removing some of the non-plastic material.
- d. By the addition of substances which on decay produce a weak acid. (peat, lignite)
- e. By adding a colloidal gel. (starch, dextrine, gelatin, etc.)
- f. By adding a weak acid to develop the gel condition. (acetic, tannic, humic)
- g. By the addition of any flocculating agent.

h. By grinding, pugging, and ageing.

Sometimes a clay is too sticky and has to be reduced in plasticity. The following methods are used:

- a. By removing or adding a suitable amount of water.
- b. By insufficient mixing of the clay and water.
- c. By adding a non-plastic ingredient. (sand, grog)
- d. By deflocculating.
- e. By heating to a moderate temperature.

Since we have no definite understanding of the fundamental principles of plasticity, it follows that tests for degree of plasticity are apt to be somewhat inconclusive. No one test is perfectly satisfactory, but each is important in disclosing the general properties of clay.

1. The Atterberg plasticity test is based on behavior of mixtures of clay and water as the proportions vary. The condition varies through all the range from a crumbly damp powder to a quite fluid slip. It was found by Atterberg that there is a relation between the plasticity of a clay and the permissible range of the water content for the paste condition. The condition of the clay-water mixture may be divided into five states as follows:

- a. Upper limit of fluidity, where the slip flows like water.
- b. The lower limit of fluidity, where two portions of the clay paste can barely be made to flow together by jarring.
- c. The normal paste consistency, where it is most workable, is not sticky, and will not adhere to metal.
- d. The rolling limit, or the condition where it can no longer be rolled into threads by the hands without crumbling.
- e. The condition where the damp clay will not hold together under pressure. The workable range of the paste is the range from condition "b" to condition "d." Atterberg claims that the greater the range in the per cent water for these two conditions, the greater the plasticity. The colloidal condition of the clay has a direct bearing on this property. The test procedure is as follows: The clay is ground to pass a 120-mesh screen. For determining the per cent water required for condition "b," 5 grams of the clay are mixed with distilled water in an evaporating dish. A good



Fig. 1. Determination of the Lower Limit of Fluidity

paste is made by thorough mixing and kneading. The paste is divided into two sections with a spatula, forming a trough between them (Fig. 1). The dish is then rapped with the hand to find out whether the two halves will flow and unite. The proportion of water and clay is varied until the two halves can barely be made to unite. The per

cent water is then determined. The difference between the per cent water in condition "b" and "d" is the plasticity number. The greater the plasticity number, the greater the plasticity.

Data on some clays follow:

	<u>Plasticity Number</u>	<u>Per Cent Water Content</u>	<u>Volume Drying Shrinkage %</u>	
		b.	d.	
M. & M. ball clay	83.7	120.9	37.2	48.2
N. C. kaolin	14.7	56.5	41.8	23.1
Tenn. ball clay	56.3	100.0	43.7	54.5
China clay	19.4	68.0	48.6	27.1

The method is useful, but gives only approximate results.

- The Ashley dye absorption test for plasticity provides for determining the colloidal content of the clay in terms of that of a standard clay, multiplying the relative colloid figure by the per cent linear shrinkage and dividing by the Jackson-Purdy surface factor. The procedure for determining the relative colloids is as follows: 400 cc of distilled water, 20 gm. of clay, and 1.2 gm. of malachite green are introduced into a 500 cc. bottle and the mixture is agitated for one hour on the frame of a ball mill. After the solids settle, a sample of the clear dye solution is removed with a pipette and put into one of two carbon comparison tubes. The other tube contains a dye solution of 3 gm. of the dye in 1000 cc. of water. This is the same strength of dye solution as given above for use with the clay. The determination is then made of the amount of dilution of the standard dye solution necessary in order to give it the same concentration as that withdrawn from the clay mixture. From the extent of the dilution, the relative colloid figure is obtained. Data for a number of clays are given below:

	<u>Plasticity R. C. x Linear Shrinkage J. -P. Surface Factor</u>
R. C.	
No. 12 English ball clay	96.5 6.52
Edgar sagger clay	69.5 3.51
Paul Clay Co. sagger clay	40.5 2.63
Pennland N. C. kaolin	25.8 1.117
Delaware kaolin	18.5 0.556

Tennessee ball clay No. 10 is used as the standard. Its R. C. value is 100.

Example:	50 gm. Tenn. ball clay No. 10 *	50 gm. unknown sample
Original concentration of malachite green	3.0 gm./1.	3.0 gm./1.
Final concentration	2.5 gm./1.	2.6 gm./1.
Amount adsorbed	0.5 gm./1.	0.4 gm./1.

Relative colloids Tenn. ball clay No. 10 = 100

Relative colloids unknown clay = $\frac{0.4}{0.5} \times 100 = 80$

- Strength tests for plasticity consist of making test bars of the clay and determining their bonding power in terms of the load required to break them. It is assumed that bonding power and plasticity are both determined by the colloid content and, for that reason, bonding power is an indicator of plasticity. This is true only in an approximate degree.
- The viscosity of the clay in slip form is sometimes used as an indication of plasticity. The more plastic clays develop more viscosity. The relationship, however, is not very definite.
- The Stringer and Emery compressibility test is more satisfactory than the two previously mentioned tests. The clay, in paste condition, is formed into a sphere 2 cm. in diameter. It is then slowly flattened until cracks appear. The more plastic clays can be flattened the most.
- The modified Bingham Plastometer method is the most satisfactory yet devised. It has the advantage of being a direct test of plasticity and subject to satisfactory control. The test is based on the principle worked out by Bingham for oils. The fundamental factors are "yield value" and "mobility." The yield value is the minimum force required to start the paste flowing. The mobility is the rate of flow. Mobility is not a function of yield value. That is to say, the yield value is not the force required to move clay at a certain mobility or rate of flow, but is the minimum force required to overcome internal friction and start the clay moving. In comparing two clays, the percentage of water in each clay is adjusted until they both have the same mobility. The one having the higher yield value is the more plastic. Plasticity may also be compared by varying the consistency of the clays until they have the same yield value; then the one having the greater mobility is the more plastic. Measurements of mobility and yield value are made in a small capillary tube having a radius of .05857 cm. and a length of 4.612 cm. This tube is connected through a stopper to a cylindrical glass container which holds the paste and which, in turn, is connected through a series of pipes to a pressure gauge and a tank of compressed air (Fig. 2). The pressure required to start the paste flowing through the tube can be read from the gauge, and the amount flowing out in a given time is determined and weighed. These are yield value and mobility respectively.

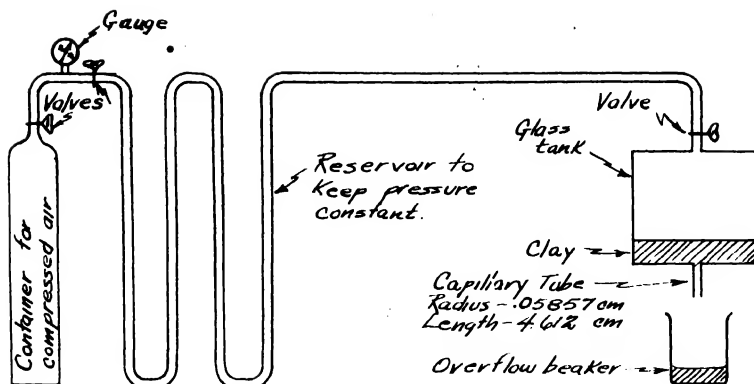


Fig. 2. Modified Bingham Plastometer

The testing procedure is as follows: The clay, finely ground, is thoroughly mixed with distilled water and placed in the container. A pressure high enough to make the paste flow is applied and the amount that flows out in a given time is determined. Then a higher or lower pressure is applied and the discharge determined. This is repeated, using several other pressures. A curve is plotted, using the pressures as abscissae and the volume discharges as ordinates. With the exception of the lower part, the curve is always straight. Then another clay is tested in the same way and its consistency is varied until the curves are parallel. This means that they have the same mobility. By extending the curves on to the abscissa axis, the relative yield values can be read. This indicates their relative plasticity. If the consistencies of the clays are varied until their yield values are the same, the curves are not parallel, but slope at different degrees. The relative plasticities are indicated by the relative slopes of the curves. Examples of yield value and mobility curves are given in Figs. 3 and 4.

Viscosity is the property of clay which is manifested in the slip condition. It is defined as the resistance to flow offered by a liquid. It is the opposite or reciprocal of fluidity. Viscosity of clay slips is measured by the resistance to the flow of the slip through an orifice, or by the resistance to the motion of a body in the slip.

The Marriott viscosimeter (Fig. 5) consists of a tube, preferably brass, 8-in. long and $2\frac{3}{8}$ -in. in diameter, fitted with a screw cap on each end, one having a hole $\frac{3}{32}$ -in. in diameter in the center and the other carrying a small tube which extends down into the larger cylinder about $\frac{3}{4}$ of its length. This inner tube permits air to enter as the slip flows out and equalizes the pressure. The slip, after being thoroughly blunged, is introduced into the cylinder with one cap already in place; the other cap is screwed on, and the time is determined with a stop watch for 200 cc. of the slip to flow out. The time is then determined for 200 cc. of water to flow out. Details of the procedure are as follows:

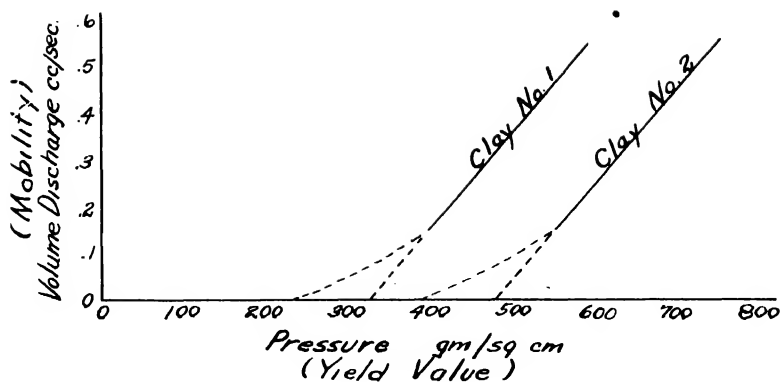


Fig. 3. Mobility Constant, Yield Value Varies

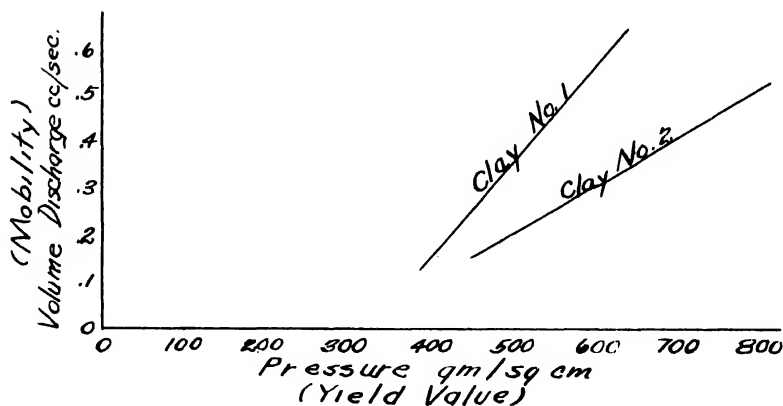


Fig. 4. Yield Value Constant; Mobility Varies

- a. Blunge the clay into a slip without grinding.
- b. Invert the container and fill with slip about 6 in. deep. Screw on the top and, holding finger over aperture to prevent slip from flowing out, turn container right side up.
- c. Remove finger and note time for 200 cc. of slip to flow out.
- d. Determine time for 200 cc. of water to flow out.
- e. Determine the specific gravity of the slip with a pycnometer.
- f. Determine the relative viscosity from the following formula:

$$\text{Relative Viscosity} = \frac{T_s \times \text{spec. gravity}}{T_w}$$

Where T_s = the time in seconds for 200 cc. slip to flow through the Marriott tube

T_w = the time in seconds for 200 cc. water to flow through the Marriott tube

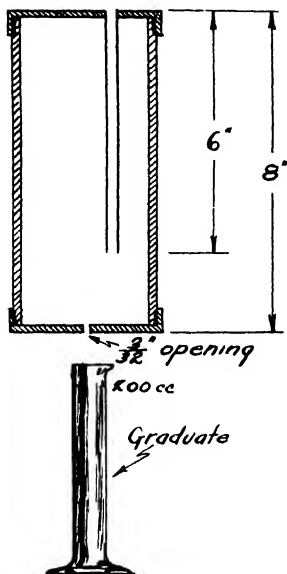


Fig. 5. Marriott Viscosimeter

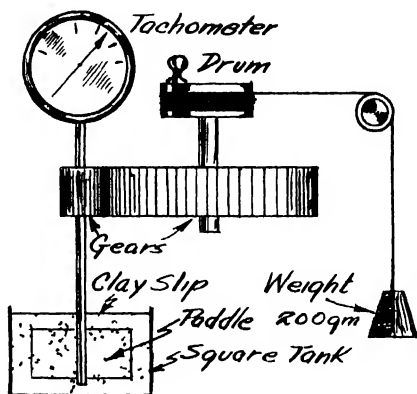


Fig. 6. Stormer Viscosimeter

The Stormer viscosimeter (Fig. 6), in contrast with the Marriott, which utilizes the principle of resistance to flow out of an orifice, utilizes the principle of resistance to the motion of a body in the slip. The slip is placed in a container and a paddle attached to a vertical shaft is lowered into the slip. The shaft is geared to a pulley which is revolved by means of a string and weight. The procedure is as follows:

- Determine the no. of sec. req'd. for 100 revolutions of the paddle in the slip = T_s
- Determine the no. of sec. req'd. for 100 revolutions of the paddle in water = T_w
- Determine the no. of sec. req'd. for 100 revolutions of the paddle in air = T_a
- Make sure that the same level is maintained in the tank for both the slip and water determination. It is also necessary to see that the

temperature of the slip and the temperature of the water are the same.

$$\text{Relative Viscosity} = \frac{T_s - T_a}{T_w - T_a}$$

In comparing clays in regard to the viscosity of their slips by the Stormer method it is customary to determine the viscosities of various concentrations of the slip and express results in terms of the percentage of clay required for certain viscosities. Typical curves for Stormer viscosities are given in Fig. 7.

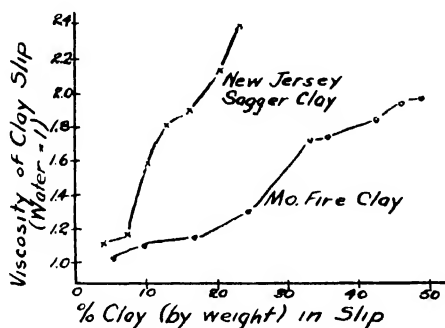


Fig. 7. Stormer Viscosity Curves for Two Clays

The Coulomb viscosimeter (Fig. 8) is similar in principle to the Stormer viscosimeter. It consists of a disc weighing 1333 gms. suspended in a container by a wire 0.85 mm. in diameter and 11 ft. 6 in. long. Attached to the disc is a pointer which revolves with the disc over a chart graduated from 0 to 360°. The resistance which the slip offers to the disc moving in it is measured. The procedure is as follows:

- The slip is first thoroughly stirred and poured into the vessel.
- The disc is then turned 180° by means of the pointer and released. The number of degrees is read off at the turning point of the vibration, so that the amplitude of each swing in the same direction is observed. This is continued until several readings have been taken.
- The disc is then stopped and the slip is stirred up for another set of check readings.
- The ratio of the amplitude of two successive swings is obtained by dividing the first reading into the second, the second into the third, and so on. The ratio is a constant for the same slip at the same temperature. It is important to keep the temperature constant.
- The time of periodic vibration is obtained by taking the total of, say, 10 complete vibrations and dividing by 20.

- f. The same procedure is followed using water only in the container.
- g. The coefficient of relative viscosity is calculated from the following formula:

$$\text{Coef. of Rel. Visc.} = \frac{T_s \log_e rw}{T_w \log_e rs}$$

Where

T_w = time of vibration for water
(time of 10 vibrations \div 20)

T_s = time of vibration for slip
(time of 10 vibrations \div 20)

rw = ratio of amplitude for 2 consecutive swings in water

rs = ratio of amplitude for 2 consecutive swings in slip

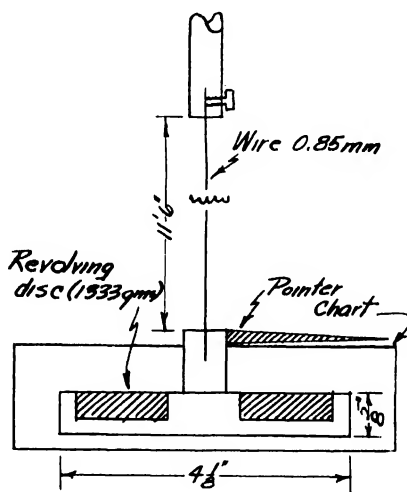


Fig. 8. Coulomb Viscosimeter

Although this apparatus is not suitable for thick slips (15% of clay maximum), the ease and accuracy with which the viscosity of thin slips can be determined makes it quite suitable for certain investigations. The viscosity of water is always used as a standard, and hence the viscosities obtained are in terms of the viscosity of water.

The Clark viscosimeter (Fig. 9) is similar in principle to the Coulomb, but is applicable to slips with high viscosities. With this apparatus, the resistance offered by a slip to a paddle revolving in it is converted into amperes and read directly from an ammeter. The apparatus consists of a vertical shaft with a paddle at one end and a hollow metal

cylinder at the other. The hollow cylinder contains an electromagnet which is caused to revolve within it by a shaft and pulley. There is a tachometer connected to the pulley shaft to measure r.p.m.

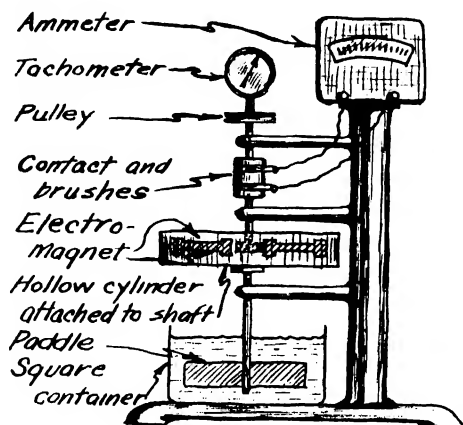


Fig. 9. Clark Viscosimeter

The clay slip is prepared and poured into the container. The magnet is revolved at a speed of 100 r.p.m. by means of the pulley and a suitable drive. Current is then passed through the windings of the electro-magnet until the hollow cylinder and paddle revolve at the same speed. This current is then read from the ammeter. The amperes are converted to torque by means of a suitable calibration curve.

The MacMichael viscosimeter (Fig. 10) is also similar in principle, except that in place of a paddle revolving in a bath of slip, this apparatus has the slip revolve while the paddle is immersed in it. The slip is introduced into a hollow brass cylinder, water jacketed to keep the temperature constant, and the cylinder is revolved by a pulley drive. The paddle is suspended by a tension wire and the twist on the wire induced by the turning force on the paddle is dampened by means of a pair of magnets and a metal disc. The degree of twist of the wire is read from a graduated disc and noted as degrees viscosity.

The bonding power of clay. Clay is self-bonding to a remarkable degree. The colloidal clay sets in drying, binding the larger grains together. The interlocking of the grains also contributes to the strength developed. Inasmuch as the colloidal content of the clays varies, their bonding power varies.

The Bischof test for bonding power consists of mixing a clay with standard sand in varying proportions, making it into a paste with water, drying it and rubbing it with the fingers. The clay has all the

sand it will carry when a slight additional amount would result in some being discharged by the rubbing. The greater the sand-carrying capacity of a clay, the greater the bonding power. This test is not used very much for clays.

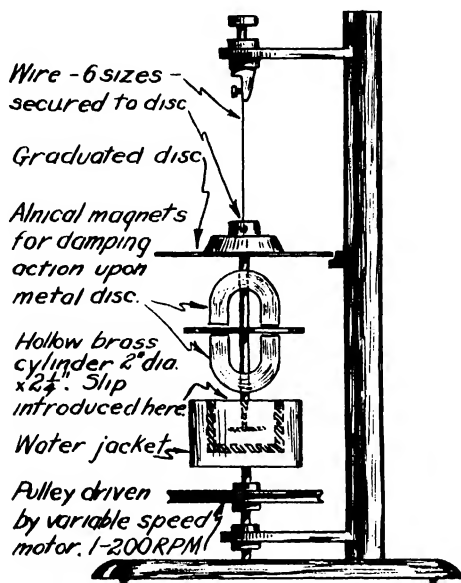


Fig. 10. MacMichael Viscosimeter



Fig. 11. Tensile
Strength
Specimen

The tensile-strength test measures the strength of a dried test specimen as a means of determining bonding power. Strength must be distinguished from brittleness, friability, and flexibility. It is the resistance to rupture under stress. The test consists of applying a gradually mounting stress until the specimen is pulled apart. The load required to pull the specimen apart, expressed in pounds per square inch, indicates the tensile strength.

The test specimen is prepared by grinding a sample of the clay through a 20-mesh screen, tempering with enough water to yield a paste of maximum plasticity, and molding the specimen in a brass mold 1 in. thick, 3 in. long, 1 11/16 in. wide at the ends and 1 in. wide at the middle. Fig. 11 illustrates the shape of the molded specimen. The specimen is then dried carefully at room temperature, followed by oven drying to

constant weight at 110°C. The breaking of the specimen consists of placing the dried specimen in the jaws of a tensile-strength machine and applying a load at the rate of 100 lb. per sec. until failure takes place. The total load required to break the specimen is then obtained and the cross sectional area of the specimen at the point of rupture is measured. The load per square inch can now be calculated. Twenty specimens of each clay should be broken, and the average tensile strength taken. Errors in the determination may arise from the following causes:

- a. Failure to break square at the point of smallest dimension.
- b. There may be flaws in the specimen from air bubbles, laminations, or cracks. This would cause the specimen to break at too low a load.
- c. Drying strains will develop if the specimen is dried too rapidly, thereby yielding too low a value.

The effect of drying in different ways is shown by the following data on tensile strength:

Clay	Air dried	Dried at 55°C. for 24 hrs.	Dried at 110°C. for 24 hrs.	Dried at 110°C. Cooled in a dessicator
	<u>lb./sq. in.</u>	<u>lb./sq. in.</u>	<u>lb./sq. in.</u>	<u>lb./sq. in.</u>
Ball	37.5	59.4	63.4	130.5
Ball	32.9	34.9	38.7	69.8
Crucible	69.1	70.6	76.1	87.8
Slip	46.1	51.2	57.3	79.2

The transverse strength test is used more than any other for bonding power. The specimens are made in a brass mold of 1 sq. in. cross section and about 7 in. in length. The molding and drying process is the same as for tensile strength specimens. The dried bars are supported on knife edges about 5 inches apart and a load is applied on a knife edge on top of the bar, midway between the supporting knife edges. The load is applied at the rate of 100 lb. per minute until the specimen breaks. The bars are carefully measured at the point of fracture for width and depth. The transverse strength or modulus of rupture is calculated from the following formula:

$$M = \frac{3Pl}{2bd^2}, \text{ where}$$

M is the modulus of rupture in pounds per sq. in.

P is the breaking load in pounds

l is the span in inches between the supporting knife edges

b is the width of the specimen at the point of fracture in inches

d is the depth of the specimen at the point of fracture in inches

Sometimes the tests are made on specimens having standard Ottawa sand added in equal amount by weight. The following data show the effect of the sand on the modulus of rupture:

<u>Clay</u>	<u>M without sand</u>	<u>M with sand</u>
Ball clay	375-558	242-330
Plastic fire clay	484-520	216-280
Shales	311-403	178-237
Plastic kaolins	239-325	122-210
Primary kaolins	74-166	53- 82

Compressive strength is a third strength test that is sometimes used for bonding power. In this test, the specimens are made into cubes 2 in. square and dried as for other tests. They are capped on two opposite sides with cement, gypsum or sulfur to make the two faces parallel. In the testing machine, they are subjected to a gradually increasing load until they crush. The results are calculated in pounds per square inch.

The slaking of clays offers a means of distinguishing between certain types. When a lump of clay or a molded specimen is immersed in water, the mass crumbles down into a slip. Some clays slake very fast, some very slowly. Some flint clays will not slake at all; bentonite clays tend to swell. The slaking test is made as follows: Test pieces shall be cubes made of a mixture of 50% by weight of ground flint, and 50% of the clay to be tested. The clay shall be all minus 30-mesh and the flint all minus 100-mesh. The specimens shall be made in the form of 1-inch cubes and dried (a) at room temperature until air dry, (b) between 64°C. and 76°C. for five hours and (c) at 110°C. to constant weight. They shall be cooled to room temperature in a dessicator. After the specimens have been dried and cooled, they shall be placed on a 2 1/2-mesh screen and carefully immersed in water at a temperature of 25°C. \pm 1°C. The water shall be at least 1 in. deep under the test piece and the top of the test piece shall be covered to a depth of not less than 1/2 in. and not more than 1 in. The time required for the whole piece to slake and settle through the screen is noted. The time reported shall be the average of the two determinations.

The odor of clay is noticeable when moist, but is lost when the clay is heated.

Clays have a characteristic feel. It is described as being soapy or unctuous. This characteristic varies with the kind of clay, the more plastic ones having the property in the most pronounced degree.

Texture is one of the most important properties of clays and body mixes. It refers to the size of grain, and shape and grading of the grains. The texture has an important bearing on porosity, shrinkage, strength, workability and other properties.

The shape of the grain is determined largely by the kind of mill used for grinding. Flaky grains tend to orient themselves in one direction, producing a lammellar structure and cause cracks; round grains will

not interlock and develop mechanical strength; angular grains interlock, but they require more bonding material. Angular grains do not transmit pressure as effeciently as round grains, and therefore account for irregular densities. Thus, different shapes of grains are required for different uses. Coarse grains account for relatively low porosity, but large pore spaces and high permeability. Fine-textured bodies have a higher porosity, but lower permeability. They also have better plasticity and workability. In the fired state, fine-textured ware is stronger, less resistant to spalling, and has higher shrinkage. Fine grained bodies fuse at lower temperatures.

The grading of the grains is important. The lowest porosity in the green state is obtained by combining batches of different grain sizes in such proportions that the voids between the coarsest grains are just filled by the material of next finer grain size and voids left are similarly filled by material of the next grain size, and so on.

The fineness of grain may be determined by screening, elutriation, air separation, sedimentation or, in the case of very fine sizes, microscopic measurement.

Screening is the most commonly employed process for sizing materials. In making a laboratory screen test, the screens are arranged in nests, one above the other, the coarsest at the top. The material to be screened is poured on the top screen and the screens are given a vibrating and semi-rotating movement. This may be done by hand or with a machine called the Ro-Tap machine (Figs. 12 and 13). The material separates on the several screens according to the size of grain. The bottom pan is solid to retain the finest size. By weighing the total, and each fraction, the percentage of each fraction can be obtained.

The screen is a band of brass, across the bottom of which is stretched the woven metal cloth. Copper, brass, and phosphor-bronze screens are used. Iron may be used in the coarser sizes. The fine mesh screens are very delicate and should never be rubbed. Neither should very coarse material be placed on them.

For a long time there was no standardization of the size of screen openings. The result was that correlation of results obtained in different places by different people was impossible. In recent years there has been an agreement on 6 standard series of screens which differ systematically from one screen to another, in size of opening and size of wire. The two most commonly used series, the Tyler and U. S. Standard, will be discussed in another section.

Elutriation, also called hydraulic classification, is a process for separating particles of different sizes or densities by suspending the material in a liquid and causing the liquid to flow at such a velocity that the finer grains are carried off, leaving the coarser grains to settle. The basis of the separation is fineness of grain, but when there is a great variation in the densities of the various materials, that factor enters also. For very exact work, flocculation should be avoided with the use of distilled water and the temperature should be kept near 15°C.

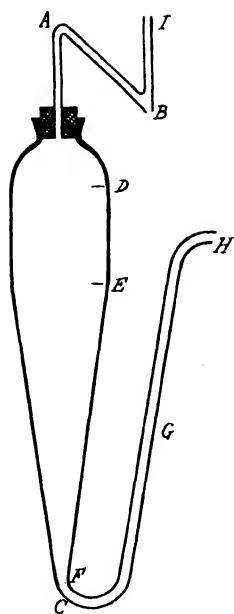


Fig. 14. Schoene Elutriator

The Schoene elutriator (Fig. 14) consists of a glass tube 60 cm. long. The upper 10 cm. is cylindrical and the section from "E" to "F" tapers to 5 mm. at the bottom. The rubber tube "G" is 5 mm. in diameter and a rubber stopper at the top holds the overflow tube "A" in place. At "B" there is a smooth round opening 1.5 mm. in diameter, and the arm "I" is made of barometer tubing and has a uniform bore. The arm "I" is about 1 meter long and is graduated in centimeters, the lowest 10 cm. being sub-divided into mm. Bends "A" and "B" must be carefully made, with no narrowing of the internal bore. At "F" there is a gauze screen to prevent coarse particles from blocking the bend "C." The tube "G" is connected at "H" to a water tank or, preferably, to a Marriott bottle and a constant flow of water can be passed through and up the apparatus. An elutriation test is made as follows:

- a. The stopper and pressure tube are removed and the vessel filled to the middle of the cylindrical portion with distilled water.
- b. Water is permitted to flow through the tube "G" at a predetermined rate.
- c. A ten-gram sample of material is introduced into the cylinder and the rubber stopper and pressure tube immediately inserted.
- d. A pan is placed under opening "B" to catch the overflow and water is allowed to flow through the apparatus until no suspended material is being carried out with the overflow.
- e. The residual matter is weighed as silt. The clay or other material carried over may be weighed or calculated as the difference between weight of original sample and residual material.

The Schoene elutriator should be carefully calibrated before use and the height of the water in the pressure tube, which corresponds to any given velocity, should be ascertained. The following procedure is used in calibrating the apparatus:

- a. The area of the section "D-E" of the tube is obtained by measuring the volume of water in section "E" to "D."

$$\text{Area} = \frac{\text{Vol. in cc. of H}_2\text{O}}{\text{Height in cm.}}$$

- b. The rate of flow for water only is obtained by measuring or weighing the quantity of water that flows through the apparatus in exactly

60 sec. and noting the height of water in the pressure tube. Then

$$\text{rate of flow in cm./sec} = \frac{\text{Volume of water}}{\text{Area} \times 60}$$

- c. If it is faster or slower than is required, the flow of water is adjusted and another trial made. After the correct rate of flow has been obtained, it is only necessary to note the height of water in the pressure tube and maintain this height throughout all future tests with the same apparatus.

Separation into different sizes is made by running at the various heights predetermined on the pressure tube. The faster the velocity of flow of water, the coarser will be the material carried out with the overflow. Standard velocities are:

<u>Velocity</u>	<u>Grain size carried through the apparatus</u>
.18 mm. per sec.	max. diameter .01 mm.
.7 mm. per sec.	max. diameter .025 mm.
1.5 mm. per sec.	max. diameter .04 mm.

The Babcock-Schultz elutriator (Fig. 15) consists of a series of copper tanks of increasing cross-sectional area, the size or diameter of the tanks being made such that the velocity in each tank can be proportioned so that each tank will separate a definite range of grain size. The tanks are arranged in series, with arrangement for the overflow

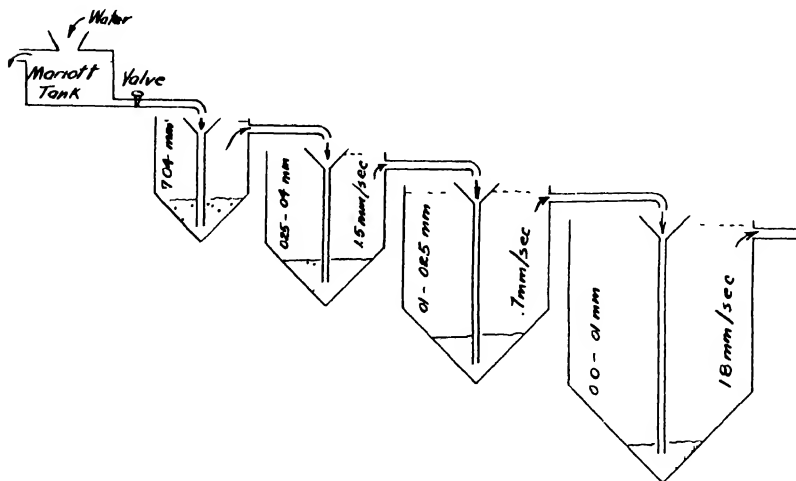


Fig. 15. Babcock-Schultz Elutriator

from one discharging into the bottom of the next larger one, and so on. The smallest tank at the beginning of the series is connected to a water tank kept at a certain level by an overflow arrangement. The water flows from this tank, at a constant head, through all of the copper tanks, the velocities in the tanks varying with their cross-sectional area. In this way, a velocity of .18 mm. per sec. is established in the largest tank, .7 mm. in the next tank, and so on. The velocities are determined by dividing the overflow in cc. by the cross-sectional area in sq. cm. and that, in turn, by the time in sec. The procedure is as follows:

- a. The flow of water is adjusted until the velocity in the largest tank is .18 mm. per sec.
- b. The sample is introduced into the first tank.
- c. Water is allowed to flow through the apparatus until the stream entering each tank is clear.
- d. The residue of material in each tank is dried and weighed.
- e. The size of material in each tank is calculated according to the velocity of flow through the tank.

Air separation is sometimes employed to separate granular materials into fractions of various sizes. The principle is similar to elutriation. A number of tanks or containers of increasing size are connected in series and air, carrying solid particles, is blown through the tanks. Due to their variation in size, the velocities of the air in the different tanks will vary accordingly. Particles of different size will settle out in the different tanks.

Sedimentation is another process for separating granular material into fractions of various sizes. Density has an effect here, as in the case of the other operations. The process consists of converting the material into a slip by blunging, and then on standing the coarse particles settle fastest and tend to accumulate below the finer particles.

The rate of settling of a particle in a liquid medium is governed by Stokes' Law:

$$V = \frac{2(D - d)gr^2}{9\eta}$$

V = velocity of the particle in cm. per sec.

η = viscosity of the liquid in centipoises

r = radius of the particle in cm.

g = the gravity constant (980)

d = specific gravity of the liquid

D = specific gravity of the particle

In dealing with clays in water, all factors except r are practically constant ($\eta = 1$, $g = 980$, $d = 1$, $D = 2.6$ approx.), therefore the velocity is proportional to r^2 .

The following table gives the time required for material of approximately 2.6 specific gravity to settle the distances given.

<u>Size of particle</u>	<u>Time of settling</u>	<u>Depth from surface</u>
.1 mm.	20 sec.	5.6 inches
.05 mm.	1 min.	4.8 inches
.01 mm.	10 min.	3.6 inches

Therefore, if a slip is allowed to settle 20 sec. and the portion above the 5.6-inch level siphoned off, all particles larger than .1 mm. will be left in the container and separated from the rest.

Specific gravity is the weight per unit volume expressed in terms of the density of water. Density, in general, means mass per unit volume, but depending upon the condition of the material there are various kinds of densities. The density of a solid bar of gold is determined by weighing it, measuring its volume, and dividing the latter into the former. In the case of most ceramic ware, the object is not solid, but porous. The true volume cannot be obtained by measuring the three outside dimensions. Account must be taken of the voids. For fired clay, using the same dry weight, we may determine:

1. Bulk specific gravity
2. Apparent specific gravity
3. True specific gravity

The bulk specific gravity is obtained by dividing the weight by the total volume, including all pores. In a fired ceramic body we have two types of pores; those which are open to the surface of the body and through which water can enter by absorption, and those which are sealed and into which water cannot enter.

The apparent specific gravity is obtained by dividing the weight by the total volume minus the open pores.

The true specific gravity is obtained by dividing the weight by the total volume minus all pores.

We have:

$$\text{bulk sp. gr.} = \frac{\text{weight}}{\text{Vol.} + \text{all pores}}$$

$$\text{apparent sp. gr.} = \frac{\text{weight}}{\text{Vol.} - \text{open pores}}$$

$$\text{true sp. gr.} = \frac{\text{weight}}{\text{Vol.} - \text{all pores}}$$

If a determination showed that a specimen weighed 196.5 gm., had 20 cc. of open pores, 5 cc. of closed pores, and 100 cc. total volume, then:

$$\text{true sp. gr.} = \frac{196.5}{75} = 2.62$$

$$\text{apparent sp. gr.} = \frac{196.5}{80} = 2.46$$

$$\text{bulk sp. gr.} = \frac{196.5}{100} = 1.96$$

The determination of volume, including all pores, varies with the character of the material. If the material is of regular dimensions, its volume may be calculated from direct measurements; if it is granular, its volume may be measured in a container; and if it is a solid of such irregular outline that it cannot be measured, its volume may be obtained by determining the pore volume and the solid skeleton volume, including closed pores.

- a. The pore volume is obtained by weighing the specimen dry, soaking it in water and weighing it fully soaked, and dividing the difference by the specific gravity of the liquid. If W = dry weight of specimen and W_s = soaked weight, then the

$$\text{pore volume} = \frac{W_s - W}{\text{s. g. of liquid}} \quad (a)$$

- b. The solid skeleton volume is the portion of the total bulk volume which displaces the liquid and, for that reason, its volume can be obtained by applying Archimedes' principle, which states that the loss in weight of a body weighed in a liquid is equal to the weight of the liquid displaced. To obtain the solid skeleton volume, we must have the dry weight of the specimen and also its weight while suspended in the liquid or W_i .

$$\text{The skeleton volume} = \frac{W - W_i}{\text{s. g. of liquid}} \quad (b)$$

- c. Combining equations (a) and (b), we have total volume including all pores =

$$\frac{(W_s - W) + (W - W_i)}{\text{s. g. of liquid}} = \frac{W_s - W_i}{\text{s. g. of liquid}}$$

Certain precautions are required in making weight determinations.

1. Thoroughly dry the specimen before determining the dry weight.
2. Make very accurate weighings. ($\pm .01$ gm.)
3. Make sure the specimen is thoroughly soaked with water for W_s . Drive out all air from the pores by boiling the specimen in the liquid and allowing it to cool with the specimen immersed.
4. Remove the surface film of water with a damp cloth before weighing the soaked specimen.
5. Operate fast enough to avoid loss of weight by evaporation.

Usually water with a spec. grav. of 1 is used, but in working with raw clay a liquid such as kerosene, which would not slake the clay, is used.

The total volume minus all pores is obtained by the use of a pycnometer. The pycnometer (Fig. 16) is a small glass bottle fitted with a ground glass stopper. The stopper has a fine capillary hole through it, and a short capillary tube extending from the top.

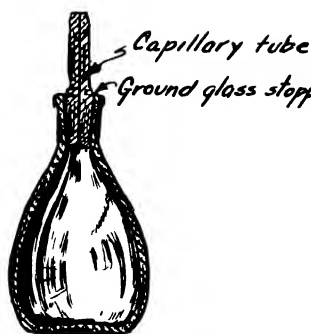


Fig. 16. Pycnometer Bottle

The procedure is as follows:

1. Grind the sample to a fineness of minus 200-mesh in order to open up all of the closed pores.

2. Obtain the following weights:

P = wt. of pycnometer empty after cleaning and drying

W = wt. of pycnometer plus sample

W_1 = wt. of pycnometer plus water

W_2 = wt. of pycnometer plus sample, plus water

About 2 gm. of the sample are placed into a previously weighed pycnometer and the bottle filled to approximately one third its capacity with distiller water. The stopper is put in place, and the water and sample boiled carefully for 15 minutes to expel any air in the

sample. The bottle is cooled to $20^{\circ}\text{C.} \pm 1^{\circ}\text{C.}$ and filled to the top of the capillary tube. The bottle is wiped dry with a soft cloth and the final drop of water at the top of the capillary tube removed with a small piece of filter paper.

3. The true specific gravity =

$$\frac{W - P}{(W - P) - (W_2 - W_1)}$$

If a liquid other than water is used, it is necessary to take into account its specific gravity. However, the slaking of the sample by water makes no difference and, for that reason, other liquids are rarely used.

The true specific gravity of raw clays varies very little except when a large percentage of heavy impurities is present. The bulk specific gravity varies with the porosity as well as impurities, but usually falls within the range 1.52 — 2.00. As ware is heated the porosity decreases, and the bulk specific gravity increases. Coarse textured bodies are relatively low in bulk specific gravity. Certain minerals in clay, such as quartz, undergo volume changes on heating, which are accompanied by changes in the true specific gravity. This is one of the ways of following the effect of heat treatment.

The Jackson-Purdy surface factor. The surface factor is a means of expressing the composite texture or fineness of granular material. After the material has been separated into fractions of various sizes by screening, and the per cent of each size obtained, it is desirable to have a single composite figure to express the average or composite fineness. The surfaces per unit volume of spheres and cubes vary inversely as their diameters. The reciprocal of the average diameter of any group of grains is taken as the surface factor. To obtain the Jackson-Purdy surface factor:

1. Determine the average diameter for each group of sizes.
2. Determine the surface factor for each group by inverting the mean diameter of each group.
3. Multiply the surface factor of each group by the percentage weight of the group.
4. The surface factor of the entire sample equals the sum of all the results of No. 3.

Example:

Diameter mm.					
Group	Max.	Min.	Av.	%	Surface Factors
1	.12	.04	.08	10	$\frac{100}{8} = 12.50 \times .1 = 1.25$
2	.04	.025	.0325	20	$\frac{10000}{325} = 30.77 \times .2 = 6.15$
3	.025	.01	.0175	20	$\frac{10000}{175} = 57.14 \times .2 = 11.43$
4	.01	0	.005	50	$\frac{1000}{5} = 200.00 \times .5 = 100.00$
					Composite surface factor = 118.83

Clay, being an aggregation of grains, has porosity. Porosity is most prominent in the green state, but persists through the firing operation, up to the last stages of vitrification. Porosity determines to a large extent such properties as strength, insulating value, resistance to spalling and resistance to slag action. It also indicates the thermal maturity of ware in firing, because porosity usually decreases with increase in heat treatment.

The true porosity is the ratio of the volume of open pores plus closed pores to the total volume. It is used very little in ceramic technology.

Apparent porosity is the ratio of the open pore volume to the total volume.

$$\% \text{ Apparent porosity} = \frac{\text{open pore volume}}{\text{total volume}} \times 100$$

The open pore volume is obtained by subtracting the dry weight of the specimen from the soaked weight and dividing by the specific gravity of the liquid, $\frac{W_s - W}{\text{s. g. liquid}}$. The skeleton volume is obtained by subtracting the immersed weight from the dry weight and dividing by the specific gravity of the liquid, $\frac{W - W_i}{\text{s. g. liquid}}$. The total volume is $\frac{(W_s - W) + (W - W_i)}{\text{s. g. liquid}}$ and % apparent porosity =

$$\frac{\frac{W_s - W}{\text{s. g. liquid}}}{\frac{(W_s - W) + (W - W_i)}{\text{s. g. liquid}}} \times 100$$

which, simplified, is equal to

$$\frac{W_s - W}{W_s - W_i} \times 100$$

Volumeters are used also in determining bulk volume. The specimens are thoroughly soaked, introduced into the volumeter filled with liquid, and the overflow of the liquid measured. The specific gravity of the liquid does not matter.



Fig. 17. Ludwig Volumeter

The Ludwig volumeter (Fig. 17) is simply a glass jar with a stoppered outlet at the bottom. The container is filled with water to the marks "A-A." About half of the water is then drained off into a beaker and the sample introduced into the container. Water from the beaker is poured back into the container until the level once again reaches the mark "A-A." The volume of the water remaining in the beaker is equal to the volume of material being measured.

The Seger volumeter is similar to the Ludwig, but more accurate and has provision for measuring the volume of displaced liquid (Fig. 18). The container is filled with water to the mark "A-A." Some of the water is removed from the container by sucking it into the bulb at the top of the burette. The sample is introduced into the container and water from the burette is returned to the container until the level is again at "A-A." The volume of water remaining in the burette can be read directly and is equal to the volume of the sample in the container.

The Schurecht volumeter (Fig. 19) is the most accurate and most commonly used. The liquid in the container is brought to the level of the overflow tube. The sample is carefully placed in the container, and the displaced liquid overflows and is caught in a burette where its volume is measured directly. The volume of the displaced liquid is equal to the volume of the sample.

The porosity of ware is affected by (a) the packing or grading of the grains, (b) the fineness of the grains, (c) the shape of the grains and (d) the forming process and forming pressures. As clay wares are fired to progressively higher temperatures, the per cent porosity decreases to a point where the ware begins to be overfired and then increases. Shrinkage, on the other hand, increases to the point of overfire and then expansion starts to take place. Fig. 20 gives typical shrinkage and porosity curves.

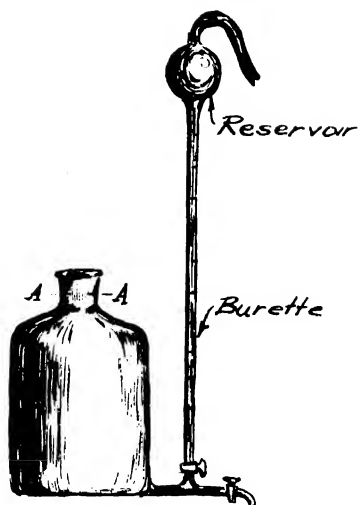


Fig. 18. Seger Volumeter

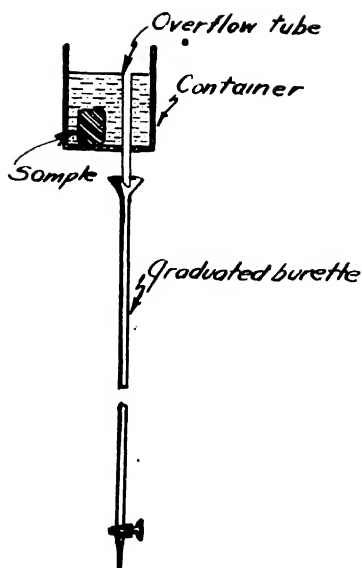


Fig. 19. Schurecht Volumeter

When a plastic clay body dries, it shrinks. It also shrinks on firing. Thus, there is drying shrinkage and firing shrinkage. In drying shrinkage, the surface tension of the film of water on the surface

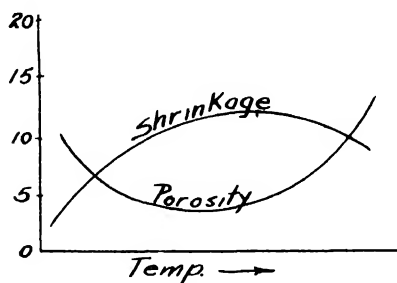


Fig. 20. Typical Shrinkage and Porosity Curves

of the grains draws them together as water is removed from between them. At the same time, the colloidal gels cement the grains together, developing strength. Similarly, in the firing shrinkage, the surface tension of the film of melted material on the surface of the grains draws them together, the strength of the finished product being due mainly to the solidifying of the ~~of the~~ melted material between the grains forming a glassy bond.

The amount of shrinkage, both drying and firing, varies with the material. It may be vanishingly small or as high as 25%. The filler controls drying shrinkage. If shrinkage is excessive and too fast,

drying cracks develop and it is the function of non-plastic material such as grog or flint to reduce the drying shrinkage and lessen the tendency to crack. The effect of filler is brought out by the following data:

<u>Clay</u>	<u>% Water</u>	<u>% Shrinkage</u>	<u>Tensile Strength</u>
New Jersey	32.6	5.3	108 lb./sq. in.
plus 50% sand	15.6	3.3	65 lb./sq. in.

The measurement of shrinkage may be linear or volume. The linear shrinkage is measured by forming a test bar or briquette of the clay and marking two lines across the bar 3 in. apart. After drying or firing, the distance between lines is measured, and the per cent linear shrinkage is expressed as follows:

$$\% \text{ linear shrinkage} = \frac{\text{length green} - \text{length dry or fired}}{\text{length dry}} \times 100$$

The volume shrinkage is obtained by measuring the volumes before and after shrinkage with a volumeter, and substituting in the following formula:

$$\% \text{ drying shrinkage} = \frac{\text{green volume} - \text{dry volume}}{\text{dry volume}} \times 100$$

$$\% \text{ firing shrinkage} = \frac{\text{dry volume} - \text{fired volume}}{\text{dry volume}} \times 100$$

The % volume shrinkage may be converted into % linear shrinkage by the following formula:

$$\% \text{ linear shrinkage} = 100 \left[\sqrt[3]{\frac{b}{100} + 1} - 1 \right]$$

where b = volume shrinkage.

A plastic clay body contains four distinct categories of water.

- Shrinkage water is that part of the free water which is removed during that period of the drying cycle in which shrinkage takes place.
- Pore water is the free water remaining in the pores of the mass after shrinkage has ceased.
- Hygroscopic water is the thin film of water surrounding the grains which can be removed only at elevated temperatures.
- Chemically combined water is the water of crystallization which is driven off in firing and which, on being driven off, leaves the clay changed in nature.

When a plastic clay body dries, the shrinkage water is first removed by evaporation, and shrinkage takes place as water is removed and the grains are allowed to draw closer together. When shrinkage has ceased

and the individual grains have packed together as much as they are able, there still remains pore space between the grains, and this pore space contains water. As drying continues, the pore water is brought to the surface by vapor tension and evaporated therefrom, but no further shrinkage takes place. In the early stages of firing, the hygroscopic water is driven off and finally, at elevated temperatures, the chemically combined water is lost. Firing shrinkage begins to take place as the liquid phase begins to form and continues until it reaches a maximum at complete vitrification. The shrinkage will be interrupted and change to expansion at temperatures where there is an inversion of quartz to tridymite or cristobalite, but continues after the inversion has been completed.

Deformation or softening of a clay body is the change from a rigid to a fluid condition by application of heat. Fusion likewise means the production of a fluid, but the term conveys the idea of interaction between two or more substances; that is, a fluxing action. The fusibility of refractories has a bearing on their service performance and the fusibility of any raw clay prescribes limitations to the heat treatment it shall receive when being fired. The mineralogical composition of the clay has a direct bearing upon its fusion temperature. In general, the higher the Al_2O_3 content, the higher the fusion temperature; and the higher the alkali content, the lower this temperature. Clays containing any mineral that acts as a flux will have a lower fusion point than clays which do not contain a flux, and the higher the flux content, the lower the fusion point is likely to be. Fusibility is affected by (a) the nature of the fluxes present, (b) the size of grain in the body, and (c) the homogeneity of the mixture. There are a number of indicators which are used both in industry and technology for measuring the temperature and heat treatment of clays being fired.

Pyrometric cones, sometimes called Seger cones, are the heat-treatment indicators most commonly used.

Cones are manufactured from ceramic materials and are made in the shape of triangular pyramids. The low temperature series are 1/2 in. at the base and 2 5/8 in. tall, and the high temperature series are 1/4 in. at the base and 1 1/8 in. tall (Fig. 21). They are made by grinding the mixture dry in ball mills to a fineness of 3 % on 220-mesh. The material is then kneaded with water and dextrine into a stiff paste. The cones are molded in metal molds and dried. Some are

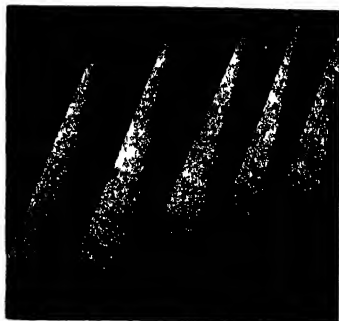


Fig. 21. Pyrometric Cones

fired slightly to make them strong. The dry press process is also being used to form cones.

Cones are used by setting them in clay plaques in regular order, inclined at an 82° angle and pointed so as to bend forward, but over the side of the plaque (Fig. 22). The numbers of the cones are stamped on the plaque under each cone. In commercial firing, they are placed in a tunnel of the setting leading to a peep hole.

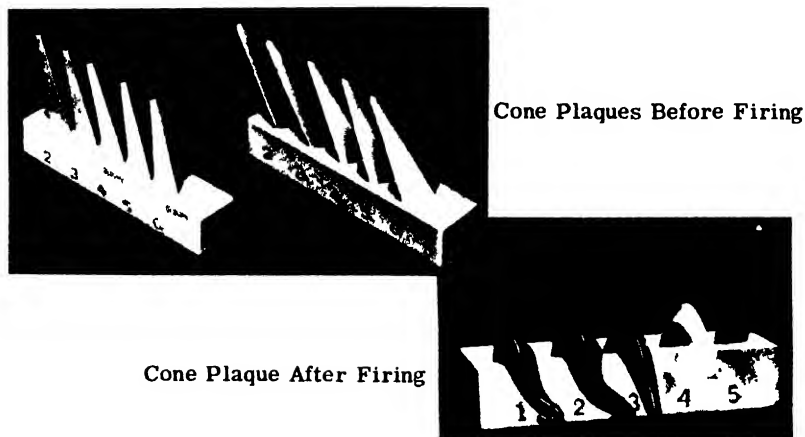


Fig. 22

The cone, under the influence of increasing temperature, develops a liquid phase that increases in amount and acquires lower viscosity as the temperature rises, until the cone can yield under its own weight and bend over. The quantity of liquid increases with time of exposure to heat. The cone thus imitates the ceramic body in its maturing or vitrification, and is an indicator of the work done on the body due to the effects of time and temperature. After a definite temperature is reached, a cone bends slowly as the temperature advances, and there is a definite time-temperature bending interval between the start of bending and the end point, or when the tip of the cone is level with the top of the cone plaque. Cones are not pyrometers, and should not be used as temperature indicators. They integrate the effects of time and temperature, so that the bending interval extends over a higher range of temperature when temperature rises rapidly, and they begin to bend at a lower temperature when the heating rate is slow.

Viscous flow is the principle governing the softening of cones. This flow will take place at a higher viscosity and the cone will come down at a lower temperature if time enough is given. Similarly, ceramic ware will develop more glassy phase with a longer soaking period in the kiln, without further rise of temperature. This is illustrated by the following table of temperature equivalents for some cones.

Cone Number	When fired slowly 20°C. per hour			When fired rapidly 150°C. per hour		
	° Cent.	° Fahr.	Bending Interval °C.	° Cent.	° Fahr.	Bending Interval °C.
1	1125	2057	30	1160	2120	45
2	1135	2075	30	1165	2129	45
3	1145	2093	30	1170	2138	40
4	1165	2129	40	1190	2174	35
5	1180	2156	40	1205	2201	50
6	1190	2174	40	1230	2246	35
7	1210	2210	40	1250	2282	60
8	1225	2237	45	1260	2300	55
9	1250	2282	65	1285	2345	115
10	1260	2300	40	1305	2381	95
11	1285	2345	70	1325	2417	80
12	1310	2390	80	1335	2435	45
13	1350	2462	70	1350	2462	55
14	1390	2534	100	1400	2552	70
15	1410	2570	85	1435	2615	115
16	1450	2642	70	1465	2669	125
17	1465	2669	75	1475	2687	125
18	1485	2705	90	1490	2714	85
19	1515	2759	100	1520	2768	70
20	1520	2768	---	1530	2786	30

The requirements for pyrometric cones are:

1. They must be inexpensive.
2. They must be large enough to be visible in glowing heat.
3. They must be so shaped as to bend slowly, so as to allow time to regulate the fire.
4. They must not be affected by chemical changes in the kiln atmosphere.
5. They must be able to endure a long, slow fire.

The cones to which some commercial products are fired are as follows:

Vitrifiable over-glazes	022-012
Face brick	2-9
White earthenware	8-9
Fire brick	5-14
Magnesite brick	16-18

To make a fusibility or P.C.E. (pyrometric cone equivalent) test of an unknown clay, a small sample of the clay is made into cones similar to the standard cones. Cones of the unknown clay are placed in the

same plaque with standard cones, and their relative behavior is compared after firing (Fig. 23). Certain precautions are important:

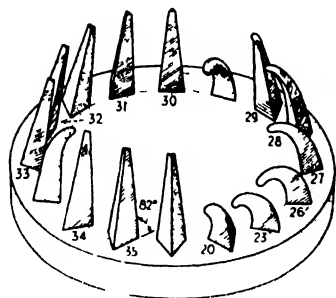


Fig. 23. Method of Mounting Test Cones and Appearance After Testing

1. Avoid cracked cones. They may break off.
2. Avoid sulfuring. A sulfur atmosphere from the fuel makes some cones swell, and others form a hard shell on the surface.
3. Avoid flashing. Direct impingement of the flame makes the cone come down too early.
4. Avoid freezing. Cones directly in front of a peep hole may become chilled while bending, and stiffen so that they will not continue to bend normally.
5. Avoid blended outlines. If placed close to a background, cones cannot be seen because they are at the same temperature as the background.
6. Avoid reduction. Reducing atmospheres change the chemical composition of the cones containing iron oxide, making them behave erratically.
7. Avoid fluxing. Fluxing vapors cause the outside of the cones to flux and melt and give erratic results.
8. Avoid volatilization. Some of the cones with volatile ingredients may suffer a loss of those ingredients if held for a long time at the softening temperature. The result is too low a value.
9. Heat at the standard rate of 150°C. per hr. up to cone 23, 100°C. per hr. to cone 39, and 600°C. per hr. thereafter. Otherwise the cones will not indicate temperature accurately.

Development of pyrometric cones. A German ceramist by the name of Seger, in 1886, while employed at a German porcelain works, thought of the idea of using cones of the same material as the porcelain as indicators. He next made a series of cones by varying the proportions of flint, feldspar, kaolin, marble, and ferric oxide, each cone of the series softening at a different temperature from the others. His cone 1 softened at 1150°C., and the highest cone of his series, cone 20, softened at 1530°C. The temperature intervals were 20°C. Later a need arose for cones softening at lower temperatures than 1150°C., and another

German ceramist introduced a series from 01 to 010. Later another German extended the range from 010 to 022. Still later, Seger extended his series upward to cone 26, and contemporary ceramists have carried the series as high as cone 42. The complete series, as we have it now, extends from cone 022 (585°C.) to cone 42 (2015°C.). Each of these cones represents an interval of temperature, provided that the time schedule of the heating is standard. The following table shows the history of the development of the pyrometric cone:

	<u>Cone</u>	<u>Melting Point</u>	<u>Composition</u>
Contemporary ceramists extended the range to this point	[42	2015°C. Al_2O_3	20 Al_2O_3 200 SiO_2
	[27	1605°C. $\begin{matrix} 0.3 \text{ K}_2\text{O} \\ 0.7 \text{ CaO} \end{matrix}$	
Seger extended range later	[26	1595°C.	
	[23	1580°C.	
ORIGINAL SEGER CONES in this range	[20	1520°C.	4 SiO_2
	[1	1125°C. $\begin{matrix} 0.7 \text{ CaO} \\ 0.3 \text{ K}_2\text{O} \end{matrix}$	
Cramer extended range lower	[01	1110°C.	3.5 SiO_2
	[010	890°C. $\begin{matrix} 0.7 \text{ CaO} \\ 0.3 \text{ K}_2\text{O} \end{matrix}$	
Hecht extended range to lowest extremity	[010	585°C. $\begin{matrix} 0.5 \text{ K}_2\text{O} \\ 0.5 \text{ PbO} \end{matrix}$	2 SiO_2 1 B_2O_3
	[022		

The composition of cone 42 is Al_2O_3 . In order to lower the fusion point by small intervals, increasing quantities of SiO_2 were added. Thus cone 41 — Al_2O_3 0.33 SiO_2 to cone 28 — Al_2O_3 10 SiO_2 . At this point, it was necessary to add an alkali as a flux to lower the fusion point further, and for cone 27 we have $\begin{matrix} 0.3 \text{ K}_2\text{O} \\ 0.7 \text{ CaO} \end{matrix}$ 20 Al_2O_3 200 SiO_2 .

The same ratio of 1:10 alumina to silica is maintained as for cone 28. From cone 27 to cone 4, the flux remains the same, and the alumina and silica are decreased by degrees, until, at cone 4, the composition is $\begin{matrix} 0.3 \text{ K}_2\text{O} \\ 0.7 \text{ CaO} \end{matrix}$ 0.5 Al_2O_3 4 SiO_2 . Cone 4 is almost the lowest temperature obtainable, with a composition of these four constituents. Fe_2O_3 and B_2O_3 were next added as follows:

Cone 3	$\left. \begin{array}{l} 0.3 \text{ K}_2\text{O} \\ 0.7 \text{ CaO} \end{array} \right\}$	$\left. \begin{array}{l} 0.05 \text{ Fe}_2\text{O}_3 \\ 0.45 \text{ Al}_2\text{O}_3 \end{array} \right\}$	4 SiO_2
Cone 1	$\left. \begin{array}{l} 0.3 \text{ K}_2\text{O} \\ 0.7 \text{ CaO} \end{array} \right\}$	$\left. \begin{array}{l} 0.2 \text{ Fe}_2\text{O}_3 \\ 0.3 \text{ Al}_2\text{O}_3 \end{array} \right\}$	4 SiO_2
Cone 01	$\left. \begin{array}{l} 0.3 \text{ K}_2\text{O} \\ 0.7 \text{ CaO} \end{array} \right\}$	$\left. \begin{array}{l} 0.2 \text{ Fe}_2\text{O}_3 \\ 0.3 \text{ Al}_2\text{O}_3 \end{array} \right\}$	$\left. \begin{array}{l} 3.95 \text{ SiO}_2 \\ 0.05 \text{ B}_2\text{O}_3 \end{array} \right\}$
Cone 010	$\left. \begin{array}{l} 0.3 \text{ K}_2\text{O} \\ 0.7 \text{ CaO} \end{array} \right\}$	$\left. \begin{array}{l} 0.2 \text{ Fe}_2\text{O}_3 \\ 0.3 \text{ Al}_2\text{O}_3 \end{array} \right\}$	$\left. \begin{array}{l} 3.50 \text{ SiO}_2 \\ 0.5 \text{ B}_2\text{O}_3 \end{array} \right\}$
Cone 011	$\left. \begin{array}{l} 0.5 \text{ K}_2\text{O} \\ 0.5 \text{ PbO} \end{array} \right\}$	$\left. \begin{array}{l} 0.8 \text{ Al}_2\text{O}_3 \end{array} \right\}$	$\left. \begin{array}{l} 3.6 \text{ SiO}_2 \\ 1.0 \text{ B}_2\text{O}_3 \end{array} \right\}$
Cone 022	$\left. \begin{array}{l} 0.5 \text{ K}_2\text{O} \\ 0.5 \text{ PbO} \end{array} \right\}$	$\left. \begin{array}{l} 2 \text{ SiO}_2 \\ 1 \text{ B}_2\text{O}_3 \end{array} \right\}$	

In recent years, the compositions and temperatures of cones have been changed so that the temperature intervals now are not uniform. There are no cones 21, 22, 24, and 25.

Professor Edward Orton introduced the use of cones into America in 1892, and, until his death, operated the Standard Pyrometric Cone Co. at Columbus, Ohio. This company is still the main producer, but there are other companies supplying the trade with cones.

✓ The Holdcroft Thermoscope is another pyroscope based upon the same principle as cones; that is, softening and deforming at the end point. They are ceramic bars of a series of compositions, placed horizontally on a refractory stair-step support (Fig. 24). The bars bend and sag to the level of the bar below. The series extends from 1 to 40. These pyroscopes are used a great deal in England, but not in this country.

Watkins' heat recorders consist of tablets of compounds that melt at different temperatures. They are placed in pockets of a refractory and their melting is observed.

The Wedgewood pyroscope (Fig. 25) is a heat-treatment indicator which is based, not on the principle of softening or melting, but on that of shrinkage. The units are all of the same composition. Shrinkage increases with increase in heat treatment. Units are removed from the kilns at various stages of the firing and their shrinkage is measured on a scale. Wedgewood scale No. 1 equals cone 022; 15 equals cone 30; 19 equals cone 41.

✓ The Veritas ring system (Fig. 26) is another pyroscope based upon shrinkage. The rings are all of the same composition, 1/4 in. thick, 2 1/2 in. in diameter, with a hole 0.85 in. in diameter. They are withdrawn from the kiln from time to time and their shrinkage is measured on a special instrument which is graduated in terms of temperatures. This is the most important competitor of the cone system.

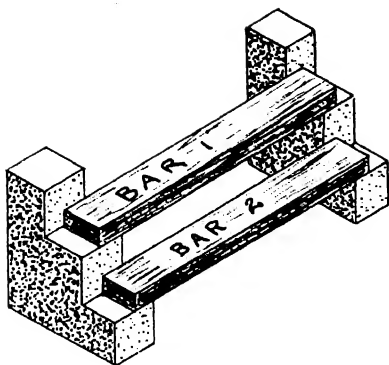


Fig. 24. Holdcroft Thermoscope

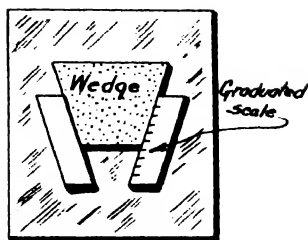


Fig. 25. Wedgewood Pyroscope

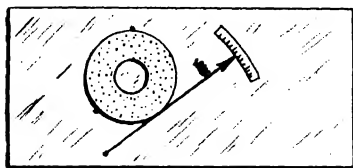


Fig. 26 Veritas Ring Pyroscope

Pyrometers are used for measuring high temperatures. The electrical thermocouple pyrometer is the one most commonly used. The thermocouple is made up of two dissimilar wires welded at one end. This end constitutes the hot junction to be inserted in the kiln or furnace. The other ends of the wires are joined in an electric instrument which measures the electromotive force generated. When two dissimilar metals are joined and the joint is heated, current will flow through a closed circuit and the voltage is proportional to the difference in temperature between the hot end and cold end of the thermocouple. It is customary to keep the cold-junction temperature constant at $0^{\circ}\text{C}.$, in which case the temperature of the hot-junction can be calibrated in terms of the voltage of the current induced. The potentiometer is the instrument which measures the voltage in the circuit.

Base-metal thermocouples, consisting of chromel-alumel or iron-constantan are used for temperatures up to $2200^{\circ}\text{F}.$ Noble-metal thermocouples of platinum-platinum plus 10 % rhodium are used for temperatures up to $2800^{\circ}\text{F}.$ The thermocouples are placed in protection tubes of porcelain, quartz, or mullite, but even then the base metals would deteriorate at high temperatures. The noble-metal couples deteriorate at temperatures above $2800^{\circ}\text{F}.$

In the Pt.-Pt. 10% Rh. couple, the positive wire is the alloy and the negative wire is the pure metal. In setting up a pyrometer, electrical connections must be + to + and - to -. Advantages of pyrometers over cones are:

- a. They indicate the rate of cooling.
- b. They indicate the rate of heating.
- c. The kiln atmosphere does not affect the results.
- d. They give a permanent record of the thermal cycle.

Disadvantages are:

- a. High cost.
- b. They give no indication of the maturity of the ware. Cones indicate the work done on the body by the heat.
- c. It is impossible to obtain readings in the center of a large kiln.
- d. They deteriorate rapidly at high temperatures.

In spite of these disadvantages, most modern kilns use many pyrometers as well as cones.

The optical pyrometer is a temperature indicator which translates the change in intensity of light emitted by a hot body with change in temperature into a temperature reading. It can be used for very high temperatures, 3000°C. or more. The optical pyrometer consists of a telescope with arrangements for focusing the light from the hot body in the kiln through lenses upon the field of vision, in which is superimposed the standard light of a filament heated by a dry cell. The instrument is calibrated in temperatures according to the current flowing through the filament. The instrument is portable, so that readings can be taken at any point. Temperatures can be taken at a distance, which cannot be done with the thermocouple pyrometer. These points, with the higher temperature readings, are the main advantages. On the other hand, kiln atmosphere affects the readings, black body conditions must be maintained, rate of heating or cooling cannot be recorded, and the human element enters.

The radiation pyrometer indicates temperature by the change with temperature of the heat radiated by a hot body. Like the optical pyrometer, it can be used for very high temperatures. It consists of a telescope in which the heat rays from the hot body are focused on a small electrical thermocouple pyrometer, the e.m.f. being measured by a potentiometer calibrated in temperatures. It has about the same advantages and disadvantages as the optical pyrometer, except that, unlike the optical pyrometer, it can be made automatically recording.

SCUMMING AND EFFLORESCENCE

Scumming and efflorescence are phenomena intimately connected with chemical composition, although firing conditions, physical properties of the clay, and other considerations, are involved. Scumming is the discoloration of ware by the deposition of a salt on the surface. There are several sources of scum. When clays that contain soluble salts are mixed with water and molded into ceramic ware, the salts are taken into solution by the water. As the ware is dried, the water containing salts in solution is drawn to the surface and evaporated, depositing the solute on the surface. Sulfates of CaO , MgO , FeO , K_2O , and Na_2O are involved. Magnesium sulfate is one of the most frequently encountered soluble salts in clays. Some clays containing pyrite will form H_2SO_4 under weathering conditions, and the H_2SO_4 in turn reacts with basic materials such as MgO , CaO , etc. to form soluble sulfates. Extremely small amounts of salts may cause serious trouble. One-tenth of one per cent is sometimes sufficient.

Scumming is often found to occur more often in the spring than at other times of the year. This is due to action of the winter frost breaking down lumps of clay containing pyrite, and to the weathering action of the spring rains, which react with the pyrite to form H_2SO_4 . The amount of soluble salts in a clay deposit is likely to vary from time to time, because ground waters entering the deposit may bring in additional salts or, in some cases, may carry away salts as they drain out of the deposit.

Scum may occur in the dryer, in which case it is called dryer scum, or it may occur in the kiln and is then known as kiln scum. Scumming is always caused by the presence of soluble salts, and the presence of soluble salts may be attributed to any one of the following:

1. Soluble salts in the raw material.
2. Soluble salts in the tempering water.
3. Scum developed from lubricating oil used on the forming machinery. In this case the lubricating oil may contain sulfur and, if it comes in contact with the clay, the sulfur with the oil reacts with Ca or Mg in the clay to form a salt.
4. Scum developed in drying. If the hot gases in the dryer, containing sulfur gases derived from the fuel, come in contact with the moist ware, H_2SO_4 is formed and in turn soluble sulfates.
5. Scum developed in burning. Soluble sulfates may be formed in the kiln from sulfur in the kiln gases in the same manner as in the dryer.

Sometimes brick may come through the drying and firing operations with no evidence of scum, but after the brick are laid in a wall, scum may develop and continue to develop even though it is removed. This is caused by scum-developing minerals in the clay brick, such as pyrite. Water which is absorbed into the pores of a brick wall during a rainstorm will dissolve soluble salts, and when it is drawn to the surface and evaporated, it will leave a scum on the surface of the wall.

For some clays, scumming is sometimes difficult to eliminate. Corrective measures are:

- a. Dry and fire the ware as rapidly as possible to reduce the amount of scum. Fast drying evaporates the water before it has time to become saturated with soluble salts. Fast firing does not give time for thorough reaction in the formation of salts.
- b. Weather and leach the clay thoroughly. Weathering breaks down pyrite chemically and leaching carries away harmful salts.
- c. Fire hard. About 70% of the sulfur will be driven off at 700°C., but only 85% at 1200°C.
- d. Introduce reducing conditions in the firing to fuse and distribute the scum.
- e. Use sulfur-free fuel in dryer and kiln.
- f. Convert the soluble salts into insoluble salts by the addition of reagents.

The last corrective is the only one which is entirely adequate. Barium sulfate is insoluble, so that if the soluble sulfates are converted into barium sulfate they cannot migrate to the surface and cause scum. The barium addition agent may be the carbonate, the chloride, or the sulfide. If the soluble chloride or sulfide is used, the amount required is the amount that can be calculated from the chemical reaction. If the insoluble carbonate is used, several times the theoretical amount is required because it is only the surfaces of the insoluble grains that are effective.

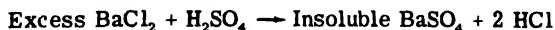
The amount of barium chloride necessary to add to a clay to prevent scumming would be determined by the following procedure:

1. Take six 500-cc. wide-mouth bottles, add 100 gm. clay to each and enough distilled water to fill them about 3/4 full.
2. Agitate by revolving on the frame of a ball mill for 1 hour and let stand for 12 hr. so that the clay may become completely disintegrated.
3. Prepare a 1% solution of BaCl_2 and add 1 cc. to the first bottle, 2 cc. to the second, and so on. Agitate again and let stand until a clear supernatant solution has formed on top of the clay. The reaction is:



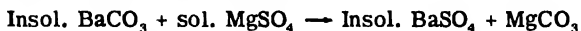
4. Pipette off a sample from the solution in each bottle and add a few drops of sulfuric acid. Of those solutions which develop turbidity

on the addition of the acid, the one containing the smallest addition of BaCl_2 has the correct amount of BaCl_2 for the clay being tested. When the BaCl_2 has reacted with all of the MgSO_4 in the clay and a slight excess of BaCl_2 remains, the addition of H_2SO_4 indicates this point by the following reaction:



To determine the amount of barium carbonate to use:

1. and 2. as for barium chloride above.
3. Add 0.1 gm. BaCO_3 to the first bottle, 0.2 gm. to the second bottle, and so on. Agitate and let stand until a clear supernatant solution forms on top. The reaction in this case is:



4. Draw off a sample of liquid from each bottle and to each sample add a few drops of BaCl_2 solution. Of those solutions which develop turbidity, the one having the least amount of turbidity contains almost the right amount of BaCO_3 . If not quite sufficient amount of BaCO_3 has been added to react with all of the MgSO_4 in the clay, then the supernatant liquid contains a slight amount of MgSO_4 in solution. This shows up on the addition of BaCl_2 as the precipitated BaSO_4 .
5. When used commercially, it is usually advisable to double the amount of BaCO_3 determined by the above procedure. This is necessary because, as previously stated, all of the insoluble BaCO_3 does not take part in the reaction.

Barium carbonate is preferred to barium chloride because an excess cannot, in itself, cause scum. The barium carbonate may be added as a dry powder to the clay, or it may be put into suspension in the water which is used for tempering.

Scumming is especially troublesome to the structural clay products industries. The presence of unsightly scum on the face of a brick building is not an uncommon occurrence. Recent investigation has disclosed that a ceramic body with 0% absorption cannot produce efflorescence, and there is likely some practical limit between 6.0 and 0% at which efflorescence will not occur. Slightly soluble as well as extremely soluble salts will cause efflorescence, however a ceramic product can contain about 0.2% of extremely soluble salts or 0.7% of the less soluble calcium sulfate before efflorescence becomes apparent.

Weathering and ageing of clays is often resorted to in order to improve their working properties and to reduce their tendency to scum. Weathering refers to the process of exposing clay, which has been loosened in the pit, to the elements of nature. Rains tend to take into solution a certain amount of the soluble salts and carry them away. The factors which affect clays during weathering are:

1. Freezing-and-thawing causes disintegration of the lumps of clay and allows oxygen and water to react with the clay.
2. Periodic rain storms cause an intermittent soaking and drying of the clay. As the water evaporates, the lumps of clay shrink and as water soaks in they tend to expand. This shrinkage and expansion breaks up the lumps of clay.
3. Water causes the clay to disperse, and colloidal material is formed.
4. Oxidizable minerals are broken down and leached out by organic acids.

Weathering increases the plasticity and workability of clays and shales. Ageing has the same effect. Ageing is accomplished by mixing the clay with water to a plastic paste and allowing it to stand over a period of time in a humidity-controlled room or under damp cloths. During the period of ageing, the water distributes itself evenly and thoroughly throughout the clay mass and better promotes the formation of colloids. Thus the plasticity and workability are increased and the tendency for thick-walled bodies to crack on firing is decreased. Fire clay for glass pots is sometimes aged for as long as 10 to 16 months.

DISTRIBUTION OF CLAY DEPOSITS

Most of the high-grade clay deposits of the United States occur in or near a large horseshoe-shaped geological formation extending from Virginia down through North Carolina, Georgia, Tennessee, Kentucky, and Missouri. Outside of this formation, other deposits occur in Pennsylvania and Florida.

Primary kaolin occurs in western Virginia as a great mantle 3 x 2 1/2 miles, covering a highly feldspathic rock which has weathered to a white kaolin, highly contaminated with secondary quartz. The most important deposits of primary kaolin occur in North Carolina, extending over into the adjoining states. It has weathered from pegmatite dikes very high in feldspar. The kaolin is worked on a large scale. Its large angular grains and low content of colloids render it a typical low-plastic kaolin.

In Georgia, important deposits of secondary kaolin occur. A belt about 40 miles wide extends across Georgia and into South Carolina. This deposit has formed from the weathering of a gravel high in muscovite, which was transported to the locality. Unlike primary kaolin, it does not overlie its mother rock, and it has a relatively high degree of plasticity.

In Florida, a deposit of secondary kaolin, quite similar to the Georgia kaolin in quality, occurs, overlaid by several feet of gravel and sand which, in turn, overlies a sticky blue clay almost impervious to water. Like the Georgia kaolin, it is of secondary origin, formed from a deposit of transported material. The deposit occurs in the north-central part of the State, covering parts of several counties.

Across the western part of Tennessee and Kentucky, an extensive deposit of high-grade ball clay occurs. This is a marine deposit. Lens-shaped formations, covering several acres, occur near the surface. The material is won by open pits in most places.

In Missouri, an extensive deposit of fire clay extends intermittently 100 miles north-east from St. Louis. Plastic, semi-flint and flint fire clays are found in this region. It is a large marine deposit, slightly less pure than the deposits of western Kentucky and Tennessee. It occurs far enough beneath the surface to require underground mining methods in most places. Small deposits of ball clay and kaolin are also found in south-eastern Missouri. The diaspore deposits of south-central Missouri are the most extensive in the world.

In western Pennsylvania, an important and extensive deposit of fire clay occurs. It is deeply buried and in most places requires underground mining. Like most fire clay deposits, it occurs under coal.

The other high-grade clays of the United States occur in comparatively small deposits. A small kaolin deposit occurs in Delaware, another in southern Illinois, and another in Connecticut. Most of the rest of the United States is devoid of high-grade clays.

Common clays suitable for making low-grade clay products occur in many localities. Almost all of the States have deposits of clay suitable for brick, tile, and other structural products.

Although no one State can be considered typical, Michigan may serve to illustrate the diversity of clays that may generally be encountered, and their wide-spread distribution. No high-grade clays are found in this State, but common clays abound. Boulder clay occurs widespread all over the State. In some places, as around Cadillac, it is 1200 ft. in thickness. It occurs in two layers, the lower layer hard and compact, the upper layer more friable. It is very stony and low-grade, and is used in only a few localities for common clay products.

The lake clays are confined to an area about 40 miles wide, extending up the eastern side of the State to Alcoma. A glacial stream flowed into a lake in this area. They vary in quality, but in most places are suitable for making brick and tile. Lime concretions abound. In some cases, the lime has been scattered throughout the deposit, but in places north-west of Detroit it has been leached out to a depth of about 9 to 12 feet, and has accumulated as concretions.

Fairly high-grade shale outcrops in two belts across the northern part of the State. The upper one is known as the Bell formation. It is a soft blue shale, 50 to 80 feet thick. It is fine-grained and quite plastic, and is suitable for brick and tile. The Atrim-Bedford shale outcrop is a belt just south of the Bell formation. It is 150 to 575 feet thick. The shale is black at the bottom and blue at the top. It contains much siderite and pyrite, much of it occurring as concretions. It weathers to a rusty appearance and burns to a very red color. On account of its high content of carbon, pyrite and siderite, care is required in its firing. This shale is in marked contrast to that of Ohio, which is very low in impurities and serves as a basis for a large brick and tile industry.

In New York, only one very small deposit of residual clay is found. It is located south-east of Sharon and is of no commercial importance. No fire clay or ball clay occurs in the State. A number of shale formations are found in various parts of the State, but only two are of any importance as a ceramic raw material. The Salina formation extends from Syracuse westward. The shale is soft, weathers easily, has good plasticity and although calcareous and contaminated with gypsum, is very useful for common red brick and other building products. Over the southern part of the State, another shale formation occurs, which at Binghamton, Elmira, and other places is suitable for common clay products. In Long Island, particularly around Glen Cove and Farmingdale, low-grade surface clays occur, suitable for making common clay products. Lacustrine clay deposits occur in the north-western section of the State, which are suitable for common brick and hollow

building tile. They are heavily contaminated with lime. The estuarine clays of the Hudson Valley are the most important in the State. At many localities along the Hudson, enormous deposits of this material occur, serving as the basis, at one time, of the largest building brick industry in the world. The deposits consist of a blue clay overlaid by a yellow weathered clay, which in turn is overlaid by a sand bed. All three materials go into the brick. The location of the deposits alongside the banks of the river, combined with the river transportation, renders the district a favorable one for supplying New York City with its building brick. The clays are laminated, plastic, red-burning, and easily fusible. Around Albany, the deposits merge into a very uniform but low-melting clay, suitable for glazing electrical porcelain. It is used for that purpose under the name of Albany slip clay.

DRYING CLAYS

Plastic clay is composed of three primary parts: (1) the cementitious, lubricating, colloidal clay portion which provides the plastic strength and shrinks with drying and loss of water: (2) the non-plastic, non-lubricating portions or grains necessary to prevent excessive shrinkage, warping, and cracking: and (3) the water films which are held onto the surfaces of all the particles and which assist in binding them into a workable mass. It is the removal of this mechanically combined water with which we are concerned in the process of drying.

Evaporation is the most important and widely used method of drying and, in its simplest aspect, is the conversion of liquid water into gaseous water vapor. Water, like all other matter, is conceived to be composed of a number of molecules. These molecules are in a state of rapid motion, the speed and extent of that motion depending upon the temperature of the matter. If, by any external means, we increase the heat energy of matter, we affect both the rate of vibration of its molecules and the position or separation of its molecules with respect to each other. If sufficient heat is applied, the molecules of water will be caused to vibrate so rapidly that they will separate, and the state of the liquid will be changed to that of a vapor or gas. This is evaporation, and the rate at which it will proceed corresponds to the rate at which heat is acquired by the water. Evaporation is the result of vapor pressure, which increases rapidly as temperature rises.

When the vapor pressure of the water within a clay body is equal to the partial pressure of water vapor in the surrounding atmosphere, a state of equilibrium is reached and no evaporation takes place. Therefore, the problem of drying clays is to provide and control an unbalanced condition between the vapor pressure of the water in the clay and the vapor pressure in the surrounding atmosphere. This is accomplished by controlling the humidity of the surrounding atmosphere, as well as the relative temperature of clay and atmosphere.

In drying, water leaves the clay as a vapor and is carried away by the air. When wet clay is placed in position to dry, there is moisture on the surface. When this surface moisture is gone, water comes from the interior of the piece to the surface, and this in turn is evaporated. The rate of evaporation is retarded, because the water comes to the surface slowly at normal temperatures. If the evaporation at the surface progresses at the same rate as the water comes naturally to the surface through the capillary tubes satisfactory and rapid drying is obtained. If the evaporation from the surface is faster, the continuous

flow of water to the surface is broken, the advantage of the capillary action is lost, and the drying proceeds very slowly. The surface is dry, but the center is wet, and the slight internal pressure developed at ordinary temperature is not enough to cause rapid drying.

The main factors to be considered in drying clay wares are (1) heat, (2) air circulation, (3) humidity of the air and (4) evaporation pressure.

Heat is used to raise the temperature of the water, clay and air to the temperature of evaporation and to change the water from a liquid to a vapor.

Air circulation mechanically carries away the vapor, and the air must come in contact with the clay surface to be dried. An air velocity of less than 300 feet per minute will not carry away the vapor as fast as it is formed. The rate of evaporation will increase with increased velocity. The rate of evaporation where air strikes directly against a surface is double that for a surface with a parallel flow of air.

The amount of moisture that air can carry varies with the temperature. Very dry air may crack the ware, while saturated air will do no drying. The carrying capacity of air when saturated at several temperatures is given in the following table:

<u>Temperature</u>	<u>Water per 100 cu. ft. of air — pounds</u>
50°F.	0.060
70°F.	0.117
90°F.	0.218
110°F.	0.384
150°F.	1.051
175°F.	1.826
200°F.	3.024

The carrying capacity of air increases rapidly with increasing temperature, and at 150°F. it will carry almost ten times as much as at 70°F. If the air carries only one-half as much water as it can carry for a given temperature, its relative humidity is said to be 50%.

Water tends to evaporate at all temperatures, and this tendency exerts a pressure which can be measured. The effective amount of this pressure depends upon the humidity of the air, as well as upon its temperature. The table below gives values for vapor pressure, known as vapor tension, expressed in inches of mercury. The effective vapor tension will be reduced in proportion to the percentage of humidity of the surrounding air.

<u>Temperature</u>	<u>Vapor tension</u>	<u>Temperature</u>	<u>Vapor tension</u>
50°F.	0.361	150°F.	7.545
70°F.	0.733	175°F.	13.650
90°F.	1.410	200°F.	23.460
110°F.	2.578	212°F.	29.920

The evaporation pressure increases rapidly with increase in temperature and tends to force the water to the surface of a clay body through the capillary tubes.

There are three stages of drying clays, involving the removal of (1) shrinkage water, (2) pore water, and (3) hygroscopic water.

Shrinkage water is the water which is removed during the period of contraction of the clay body. It is equal to the volume lost during the drying period, or the difference between the plastic and dry volumes. As drying progresses, the capillary films decrease in thickness, the grains are drawn by surface tension into close contact, and the mass as a whole is reduced in volume. This continues until a sufficient number of the particles are in contact to cause the total volume to remain constant. At this point the clay may still retain a considerable amount of its original water content.

Pore water is that which remains in the clay after the shrinkage water has been removed. It is the difference between the total water of plasticity and the shrinkage water. After the volume contraction has ceased, a large number of the capillaries have become broken, and the rate of diffusion becomes very slow. The larger grains of sand and grog are now in contact, but local shrinkage of the still wet, colloidal clay matter between the large grains can still proceed.

Hygroscopic water is the very thin film of water surrounding the colloidal particles of clay that cannot be removed at temperatures below 110°C . Often temperatures higher than 110°C . are necessary, and so the hygroscopic water is usually removed in the kiln during the early stages of firing.

In drying clay wares, it is desirable to control conditions so that the rate of moisture movement or diffusion shall be uniform throughout the mass at any given time. If a wet, plastic mass of clay were exposed to a hot, dry atmosphere evaporation would take place at the surface of the clay in excess of the rate of flow of the water from the center of the body. The effect of this would be to produce a surface shrinkage which would restrict the channels through which the water must pass from the center to the surface. The shrinkage of the surface would set up a compression upon the inner core of the body, and the strain imposed upon the surface layers of the body would produce cracking. Since, in this case, the outside of the clay body is drying faster than the inside, and consequently shrinking faster, the body will tend to warp.

The fine-ground highly colloidal clays containing a minimum of non-plastic material and a maximum of water are the most difficult to dry without cracking. The finer the grain size, the smaller is the average capillary. Capillarity will thus be unable, in many cases, to maintain a sufficient supply of water in the outer surface to replace that lost by evaporation and to maintain a uniform water content between surface and interior.

In testing clays for their drying properties, the following factors are determined:

1. The best rate of internal temperature rise of the clay.
2. The critical internal temperature from which drying can proceed at a rapid rate.
3. The maximum rate of drying after the critical internal temperature has been reached.
4. The cracking and slumping zone (where the humidity is too high) for various temperatures.

Rapid and controlled drying means rapid turnover, constant flow of ware through the plant regardless of weather conditions, smaller drying space, no setting of wet ware in the kilns, and a reduction of dryer losses.

A great deal has been written about the operation and control of commercial driers. The drying operation in any ceramic plant is of the utmost importance because almost imperceptible defects in the ware, caused by improper drying, will be magnified during the firing of the pieces.

Commercial driers may be divided into two broad classes, (1) direct heat, and (2) waste-heat dryers. These in turn can be classified as intermittent driers or continuous driers. In direct heat dryers the heat is supplied directly to the drier by burning fuel or by the consumption of electrical energy. In waste heat dryers the heat is supplied from an outside source, usually from cooling kilns.

Any dryer in which the ware remains stationary during the drying is an intermittent dryer. There are many variations of this type of dryer and they may cost from a few hundred to several thousand dollars per installation. The most elementary type of intermittent dryer is a construction of racks out doors upon which the ware may be placed to dry naturally in the sun and wind. This type of drying is practiced in many of the soft-mud building-brick industries. Some sewer pipe plants utilize a large room, provided with a slatted floor underneath which runs a series of steam pipes. Ventilation and draft is provided by opening and closing windows of the room. Refractory shapes are usually dried on a hot floor similar to that used for drying sewer pipes, except that the floor is continuous.

In smaller, completely enclosed, drying chambers the heat may be supplied by steam pipes or by blowing in hot air. Some amount of control may be had in chamber dryers by regulating the intake and exhaust fans so as to maintain a proper velocity of air through the dryer. The humidity of the air at the exhaust fan can also be controlled to a certain extent.

Continuous dryers are by far the most efficient dryers and lend themselves much more readily to manual and automatic control. In general, the construction principles of both the direct-heat and waste-heat dryers are similar except for the method of supplying heat to the ware. Direct-fired dryers are furnished with a combustion chamber and fireboxes where solid, liquid, or gaseous fuel may be burned. The combustion of fuel may take place directly at the drier or remote from

it. In the latter case the hot air must be conducted to the dryer chamber by pipes and a blower. For reasons of economy waste heat is used wherever feasible in drying clay ware.

The waste-heat tunnel dryer consists of one or more chambers each in the form of a long tunnel. The ware travels through the tunnels on cars and is progressively dried from the entrance to the exit end. Each tunnel is entirely separate from any other and may be operated independently. Hot air is introduced into one end of the tunnel by a fan, travels through the chamber containing the ware and is exhausted with the evaporated moisture at the cooler end of the tunnel. Controllable factors are the velocity of the air through the dryer, the temperature of the drying air, the relative humidity of the drying air at various points in the dryer, and the speed at which the ware travels through the tunnel. Humidity is most often controlled by recirculating some of the air from the exhaust end of the dryer. This air is carrying a great deal of moisture from the ware and is used to dilute the dry air from the source. By designing various baffles, ducts, and outlets into the dryer the path of flow of the drying air can be regulated to give the best results.

Infrared drying has found favor in many ceramic industries, although it has certain limitations. Infrared rays can be produced through infrared electric lamps or by means of infrared gas burners. To date the usefulness of the infrared dryer appears to be limited to the thickness of the ware being dried. For material more than one and one-quarter inches thick infrared drying is slow and has few advantages over the other methods. Ceramic applications of infrared drying are chiefly in the whiteware industries for drying dinnerware, electrical porcelain bodies, and pottery. Porcelain enamel can also be successfully dried by this means.

The chief advantages of infrared drying are: (1) A marked decrease in the drying time required, (2) Elimination of damage and the labor cost involved in handling and transporting ware to and from a drying room, (3) The initial cost of installation is less than most other types of dryers, (4) The fuel consumption is very low, (5) A clean dryer atmosphere is always present.

The installation of automatic control wherever possible in any type of dryer will more than pay for itself in reducing dryer loss and increasing dryer production. Controllable factors in drying are: (1) an economic supply of heat for drying, (2) the maintenance of the plasticity of the body surface until the ware is heated throughout, and (3) supplying a sufficient quantity of air to carry away the water vapor. To obtain sensitive dryer control a wet- and dry-bulb control instrument is located so that the thermometer elements are in the air stream flowing from the dryers. This instrument controls the valves in a compressed-air system which operate (1) air motors to open and close louvers which regulate the velocity and volume of air being exhausted, (2) a steam valve which will admit steam into the dryer if the relative humidity of the drying air is too low, and (3) an electric switch for a small air-tempering fan.

A dry-bulb controller may also be installed near the supply fan. This instrument controls the set of louvres, which admits fresh air for cooling at the fan intake and the set of louvres which regulates the quantity of air flowing into the dryer. A continuous record is kept on charts by all control instruments.

Chapter 10

FIRING CLAYS

Since clays, themselves, are an aggregate of minerals, and since most clay bodies consist of a mixture of clays with other ceramic raw materials, a study of the effect of heat on ceramic bodies is very complex indeed. When clay is heated, some of the compounds are broken down, water vapor and other gases are evolved, oxygen is taken into combination, some crystal phases are destroyed and new crystal phases formed. Kaolinite ($\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$) contains two molecules of water which, under the influence of heat, are driven off. This change is accompanied by an endothermic reaction, during which heat is taken up by the material, associated with an increase in molecular volume. At about 900°C . the aluminum silicate dissociates into amorphous mullite and silica and an endothermic reaction, or one in which heat is given off by the material, occurs.

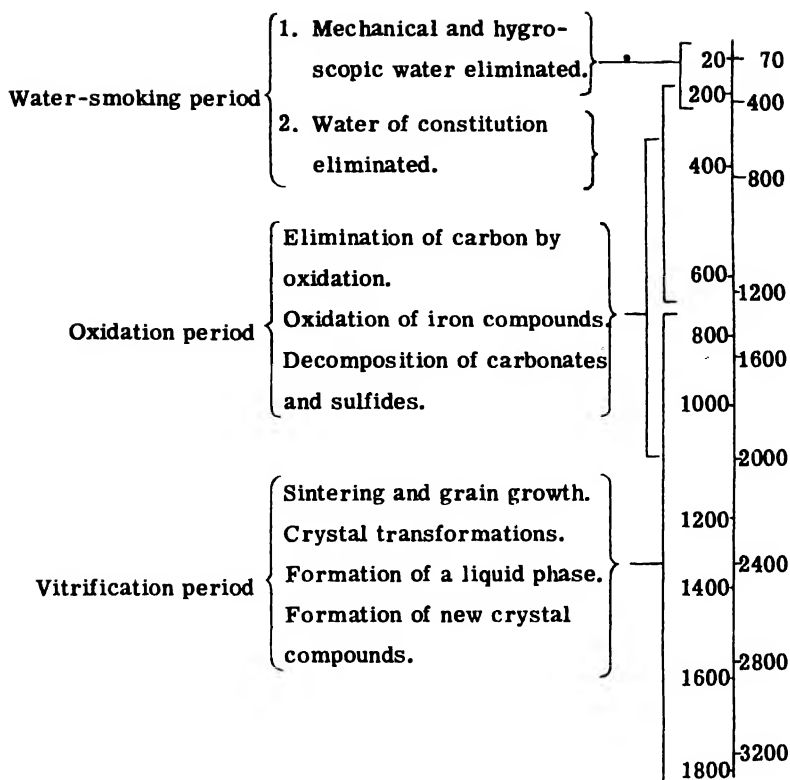
As the vitrification temperatures are reached, the external volume contracts, due to the effect of surface tension of the partially fused particles. This continues with increasing temperature until the pore spaces are practically closed, a condition which is called complete vitrification.

The firing of clay wares is ordinarily divided into three periods: (1) dehydration or water-smoking period, (2) oxidation period, and (3) vitrification period. These periods and their relative temperatures are shown in the following table:

(Table on next page)

These periods vary with different types of clays and with the impurities present. It is apparent, however, that the oxidation period overlaps both the dehydration and the vitrification periods. Most of the chemical water is driven off by the time the temperature reaches 650°C . to 700°C . Carbon begins to oxidize at about 400°C ., but may not be entirely eliminated until about 950°C .; sulfur, on the other hand, is not driven off completely until about 1150°C . to 1200°C . When the carbon content is large, the oxidation and elimination of sulfur and the oxidation of iron compounds will be retarded. Carbon has a stronger affinity for oxygen than sulfur, and sulfur a stronger affinity than ferrous oxide.

The characteristics of any clay body must be carefully studied for each of the three firing periods. Kilns are so designed to properly take care of each period. If firing conditions are not correct during the water-smoking period ware may be damaged through cracking,



kiln marking, checking or crazing of the ware surfaces, development of blisters on the surface, and the formation of a weak structure. Efflorescence may be developed, discoloring the surface of the ware or preventing the glaze from properly maturing. Firing costs will be increased because of the excess time, labor, and fuel required.

The water-smoking period is divided into two parts: (a) the mechanical dehydration period, during which any mechanical water in the ware not removed in drying and most of the hygroscopic water are driven off, and (b) the chemical dehydration period in which the water of crystallization or chemically combined water is driven off. Ware that has been properly dried may be heated as rapidly as possible, within certain limitations, during the water-smoking period. The limiting factors are attaining the proper heat distribution throughout the kiln and the amount of carbonaceous material in the ware that requires oxidation between 500° and 600°C. Most of the difficulties encountered are likely to occur during the first stage of the water-smoking period. If correct conditions have been maintained during the first stage there is little possibility of spoiling the ware during the second stage. Kiln gases contain

a considerable amount of water-vapor. When these gases come in contact with the surface of ware in the kiln which is at a temperature lower than the dew-point of the gas, condensation of water-vapor will take place on the ware. This is the primary cause of kiln marking and slumping. The formation of kiln scum will also take place if the surface of the ware is wet and there are sulfur gases in the kiln atmosphere.

In general, it is necessary to use a considerable amount of excess air during water-smoking. The use of a large volume of air helps to prevent the formation of kiln scum because any mechanical water in the ware is being evaporated and the concentration of sulfur gas in the atmosphere is greatly reduced. The volume of air used must be sufficient to maintain the dew-point of the kiln gases below the temperature of the ware surfaces in order to prevent condensation. One thousand to 1500 per cent excess air may be required at the start of the firing, but as the ware heats up, the amount of excess air may be gradually reduced to approximately 150 to 200 per cent.

The chief function of the oxidation period is to burn off any carbonaceous matter present and to break down certain compounds, chiefly those containing sulfur. Since sulfur is generally harmful in a ceramic body, it is desirable to drive off as much of the sulfur as possible during oxidation. Since the carbon has a higher affinity for oxygen it will oxidize first. Most forms of carbon will oxidize easily at relatively low temperatures provided a sufficient supply of oxygen can reach all parts of the ware. There are, however, certain forms of carbon which are very difficult to oxidize even at higher temperatures. Incomplete elimination of the carbon has often occurred because of insufficient low-temperature oxidation even though a fairly long oxidation period was allowed at higher temperatures. Common evidence of insufficient elimination of carbon is found in ware that has a black core. Black core is a dark grey to black center in any piece of fired ceramic ware. At higher temperatures gases may form in the black core and cause bloating of the ware.

Sulfur is more difficult to burn out than carbon. At 850°C. as much as 80% of the sulfur can be eliminated but even at temperatures as high as 1200°C. there may still be 5 % of the total sulfur left in the clay. Sulfur is a chief contributor to scum formation and usually occurs in the clay as iron sulfide (pyrite), as a portion of the organic material, or as a sulfate, such as gypsum.

The oxidation of iron compounds is necessary to proper firing of any red-burning product. The state of oxidation of the iron compounds produces various shades of reds. If the iron compounds are partially reduced, brown, grey or gun metal colors will result. The iron may be present as pyrite, marcasite, limonite, sulfate, carbonate, siderite, or oxide, and the temperature of oxidation will depend upon the compound present. Most iron compounds will be oxidized to some extent at 800°C. Whether ferric or ferrous oxides are formed will depend upon the amount of oxidation which has occurred. A change from either

oxide to the other may take place at any time as long as the temperature is below the dissociation temperature of ferric oxide and conditions are favorable.

During the vitrification period the grains of material in a clay body begin to melt and sinter, and a liquid phase commences to form. The temperature at which this reaction begins will depend upon the type of fluxes present. As the temperature increases, crystal transformations take place. The various crystal phases can be seen by referring to the equilibrium diagram of the system $\text{Al}_2\text{O}_3 - \text{SiO}_2$ (Fig. 27). By taking a point on the diagram corresponding to 54% silica and 46 % alumina, which is the silica-alumina ratio of dehydrated kaolin, we can follow the changes that take place with change of temperature. Between 850°C. and 1050°C. (not shown on the diagram), an exothermic reaction occurs, resulting in the dissociation of the $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ to form amorphous mullite, $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$ plus tridymite, SiO_2 . The equilibrium diagram begins with tridymite and mullite. Tridymite is a different crystal form of silica. At 1470°C. tridymite becomes unstable and inverts to cristobalite, which is the stable form of silica at this temperature, so that we now have cristobalite and mullite. At 1545°C. an eutectic between cristobalite and mullite forms. It consists of 5.5 % alumina and 94.5% silica. Here a liquid phase makes its appearance, and we have mullite and liquid. As the temperature increases, the percentage of liquid becomes greater, and the percentage of mullite decreases until, at approximately 1800°C., the mullite completely disappears and the liquid phase alone remains.

As quartz inverts to beta quartz, there is a sudden expansion of the crystals accompanied by a loss in weight, and a similar phenomenon occurs during the inversion of beta quartz to tridymite. The specific gravity of quartz is 2.65, that of tridymite 2.28-2.33. As the specific gravity decreases, the volume increases about 16 per cent. The same reaction, but to a lesser extent, takes place during the inversion of tridymite to cristobalite. These periods of inversion must be closely watched during the firing cycle, as too fast an inversion and expansion may cause strains in the body, resulting in fine cracks.

It can be seen, from the foregoing discussion, that, in order to properly fire ceramic ware, it is necessary to know what chemical and physical changes take place in the clay body, during the firing cycle. Knowing the nature of these changes, the kiln operator can so regulate his time and temperature factors to produce the best possible results.

During the water-smoking period mechanical and chemical water is driven off and some shrinkage of the ware takes place. At this point the clay grains are not cemented together very strongly and care must be taken that strains are not set up by too rapid evaporation of the water. Too rapid heating can completely disintegrate a piece of clay ware. The same precautionary measures must be taken during the oxidation period. While oxidizable materials are being burned gases are being evolved and they must escape through the pores of the body. If the heating rate is too fast, gases will be formed faster than they

can find their way out of the body, internal pressure will be built up, and the body may rupture. During vitrification, incipient fusion takes place around the grains and they are drawn closer together, resulting in shrinkage of the body which continues until nearly all of the pore space has been filled. Individual materials within the body, however, react according to their nature. Quartz, as we have seen changes its crystal form and expands at definite temperatures. Thus we have complex and conflicting reactions taking place at the same time in the clay body. The shrinkage in the body may halt, change to expansion, and later, change back to shrinkage with increasing temperature. If the ware is carried beyond its vitrification temperature, gases may be evolved, boiling of the liquid will occur, and the body will have a bloated, vesicular structure. Since most of the crystal changes are reversible, equal precaution must be exercised during the cooling period, to see that these changes do not take place too rapidly. From a theoretical viewpoint, phase diagrams (Fig. 27) provide a potentially useful method for the analysis of ceramic bodies in the fired condition. Commercial bodies contain minor amounts of so many accessory minerals, however, that it is impracticable to construct complete equilibrium diagrams. The main deterrent to the greater use of phase diagrams exists in the fact that commercial bodies cannot be economically fired for a sufficient length of time at vitrification temperatures to permit establishment of equilibrium reactions.

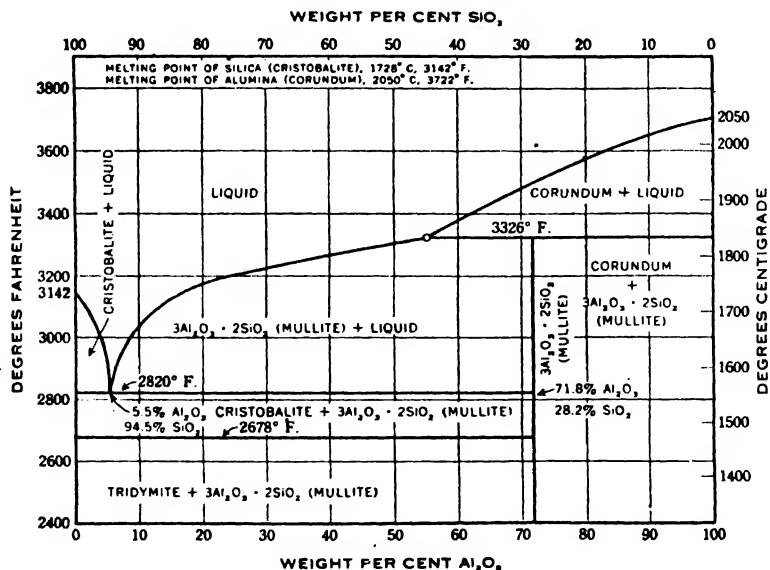


Fig. 27. Equilibrium Diagram of the Al_2O_3 — SiO_2 System (Bowen and Grieg)

There are two broad classes of kilns for firing ceramic ware: (1) periodic, and (2) continuous. A periodic kiln is one in which the temperature cycle starts from atmospheric temperature, builds up to the maximum temperature required, and then decreases back to atmospheric temperature. The ware is loaded into a cold kiln, fired, and withdrawn after cooling. Periodic kilns are wasteful of heat. Fuel is burned to heat up the brickwork structure of the kiln and this heat is lost when the kiln is cooled down after each firing. Continuous kilns are constructed so that either the ware travels continuously through sections of the kiln maintained at a nearly constant temperature or the hot gases travel through a number of chambers in the kiln while the ware remains stationary.

The simplest of all periodic kilns is the scove kiln. It is used for firing building brick and is constructed by piling up the unfired brick in such a manner as to leave spaces between the bricks through which the hot gases may rise. The brick in the outside walls are stacked tight together to prevent cold air from leaking to the interior of the kiln. Fireboxes and fire arches are built into the construction at ground level and wood, coal, oil or gas may be burned in the fireboxes. The hot gases and products of combustion rise through the setting and escape at the top. Because the gases travel upward the scove kiln is known as an updraft kiln. A new kiln must be built for each firing, however as many as one million brick can be fired in a scove kiln. The chief advantage of the scove kiln is that it is cheap to construct, since it is made entirely of the product being fired. The brick forming the outside wall and roof are underfired and must be discarded or if they are not broken may be used again for the same purpose. The brick used to make the arches and fireboxes are usually overfired and must be discarded. The labor of setting and drawing a scove kiln is simplified because workmen have access to the pile from all sides and it is not necessary to transport the ware in and out fixed doorways. The disadvantages of the scove kiln are serious. It is practically impossible to get a good even burn throughout all sections of the kiln, with the result that some brick are overfired, some are correctly fired, and some are underfired. This results in a variation of hardness and soundness, a variation in size due to differences in shrinkage, and a variation in color.

Downdraft kilns are used more often than scove kilns and have a wider variety of products that can be successfully fired in them. Almost any ceramic product can be fired in a downdraft kiln although they are generally used for firing brick, building tile, sewer pipe, stoneware and refractories. Downdraft kilns are constructed of fired common and refractory brick and may be either circular or rectangular in shape. They have permanent walls and permanent roof, built in fireboxes and a flue system in the floor that leads to a stack. Barriers, known as bag walls, are built on the inside of the kiln, a foot or two from the inside wall, and in front of each firebox. These bag walls are six to ten feet high and protect the ware from direct impingement of hot

gases or flame as well as act as a chimney to conduct the hot gases towards the roof of the kiln. When the gases reach the roof of the kiln they are pulled downward through the ware, into the collecting flues in the floor to the main flue and out the stack. A number of fireboxes are built around the kiln and these may be so constructed so as to use wood, coal, gas or oil fuel. The temperature and draft are much more easily controlled in this type of kiln and fairly high temperatures may be attained.

The most efficient of all continuous kilns is the car tunnel kiln. It consists of a long, narrow chamber with an opening at each end. The ware travels through the kiln on flat-top cars and the car tops serve as a bottom to the kiln. The kiln is divided into heat zones and each zone is regulated and maintained at a given temperature range. The ware, upon entering the kiln goes into a preheating zone where it is gradually introduced to increasing temperature until the water-smoking period is past. From the preheating zone the cars progress to the high-heat zone where vitrification and maturing of the ware takes place. Immediately following the high-heat zone is the cooling zone where the ware is cooled, as rapidly as possible, to a temperature low enough to allow handling.

The value in the car tunnel kiln lies in the ease with which it can be controlled, the remarkable uniformity of heat treatment of the ware, and the large economy in fuel and labor that can be attained. Often one setting of the cars is all that is necessary for both drying and firing of the ware. Waste heat from the cooling zone can be recirculated and used for preheating the incoming ware and for preheating the air for combustion. Tunnel kilns should be operated continuously for best efficiency. Frequent shutdowns with accompanying expansion and contraction of the structure will severely shorten the life of the kiln.

The continuous chamber kiln consists of a number of chambers or rooms connected together with mutual parting walls. This type of kiln may be either rectangular or circular. In the chamber kiln the fire progresses from chamber to chamber the heat from the cooling chamber being used to preheat the unfired ware to a temperature near to the top firing temperature. If chamber one has been fired and the ware, now cool, is being withdrawn, then chamber two is still cooling. Air is blown in from the outside through the ware in chamber two and into chamber three where it picks up further heat from cooling ware in that chamber. Let us suppose, for example, that chambers two, three, four, and five are cooling and that the air from outside reaches a temperature of 400°F. in chamber two, 800°F. in three, 1200°F. in four, and 1500°F. in five. Chamber six is under fire at 2000°F. and air for combustion is being supplied to this chamber at 1500°F. Ware in chambers seven, eight and nine is being preheated by the hot gases coming from the firing chamber. The temperature of the ware in chamber seven will be about 1800°F., that in eight, 1000°F. and the temperature of nine would be about 300°F. The ware in chamber ten is undergoing water smoking and chamber eleven is being loaded. As soon as the firing

has been completed in any chamber the fires move on to the next chamber and the whole cycle progresses thus making the system a continuous one.

By utilizing a large proportion of the waste heat the continuous chamber kiln can be operated on about one half the fuel consumption of a periodic kiln, per ton of ware. The chamber kiln is expensive and requires a complicated system of air ducts and fans in order to properly distribute the heat throughout the kiln.

WASHING, REFINING, AND BENEFICIATION OF CLAYS AND OTHER CERAMIC MATERIALS

Few clays, as found in nature are ready for use in ceramic bodies. Many clays contain impurities that must be removed by refining methods, some are lumpy and must be ground down and screened to a uniform size, while others must be treated to improve their plasticity or working properties. The treatment of clays or other raw materials to improve their desirable physical properties is called beneficiation.

Most high-grade clays such as kaolins, some ball clays, and some fire clays, when taken from the ground, contain undesirable impurities that would be harmful to the better class of ceramic wares. The impurities most often encountered are free quartz, mica or other iron-bearing minerals, rutile, and sometimes organic matter such as roots and lignite.

Clay Washing. Kaolin is mixed with about three times its weight of water and the lumps thoroughly broken down in a blunger. This treatment also helps to separate the clay from the particles of free quartz. The blunged slip of clay and water is then allowed to flow into a settling trough where the coarse sand settles out and is removed by means of a device called a sand wheel. The partly purified slip next flows into the mica troughs where most of the fine sand and the mica is removed.

The sand wheel (Fig. 28) consists of a wheel carrying a series of buckets on the circumference and revolving in a narrow trough. The buckets are perforated so as to let excess moisture drain through but the perforations are small enough to retain most of the solid material. The bottoms of the buckets may be lined with cloth if so desired. When used to remove coarse sand from a clay-water mixture, the slip is made to flow through the trough while the wheel is revolving. The buckets pick up the sand near the bottom of the trough while most of the clay is carried on through with the flowing stream. The sand is dropped from the bucket when it reaches the top of its cycle. The sand wheel is driven at about 2 r.p.m. by a 10 h.p. motor.

Mica troughs are a series of long, narrow troughs, through which the slip slowly flows while the fine sand and mica settles out. Each trough is approximately 2 x 2 x 50 ft. long, so that with a series of 14 troughs the slip will travel 700 feet. They are sloped 1 inch in 50 feet to insure that the slip will flow slowly enough to allow the impurities to settle out. Periodically, the sand and other impurities must be raked from the troughs. After the slip has passed through the mica troughs, it is

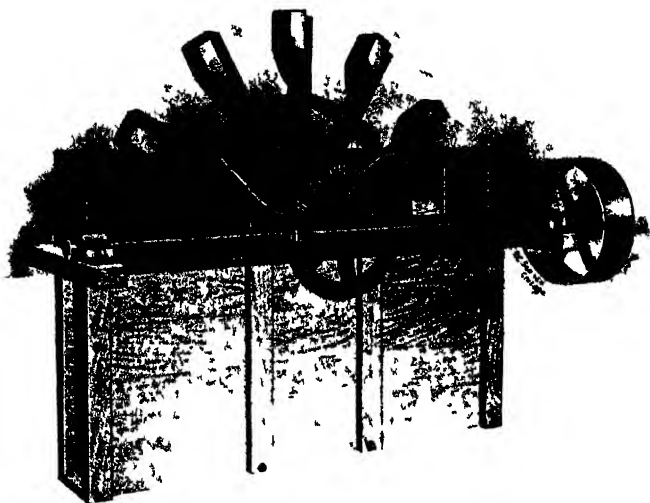


Fig. 28. Sand Wheel

screened through 100-mesh screens which remove any twigs or roots. A composite diagram of the process is shown in Fig. 29

The following precautions must be followed in washing high-grade clays

1. Do not re-use the water if it becomes saturated with soluble salts.
2. Keep the water clay ratio at 1.3 specific gravity.
3. Keep a uniform flow of water.
4. Keep the mica troughs clean. As the cross section becomes smaller, the slip flows faster and the mica will not settle out.
5. Mica troughs should be constructed of cypress, as concrete will introduce soluble salts.

A typical example of a clay-washing operation is as follows:

1. Clay is mined hydraulically and washed to the pit of a bucket elevator.
2. A wooden flume conducts the material to number one sand wheel.
3. Material passing through the sand wheel is further purified of any coarse sand in a small settling tank.
4. Partly purified clay slip goes to a second sand wheel.
5. Material passing second sand wheel is fed to a series of settling tanks where the very fine sand and mica particles are removed.
6. The purified slip is pumped into filter presses where the excess water is squeezed out.
7. The filter cakes are dried and the pure clay is ready for crushing and bagging.

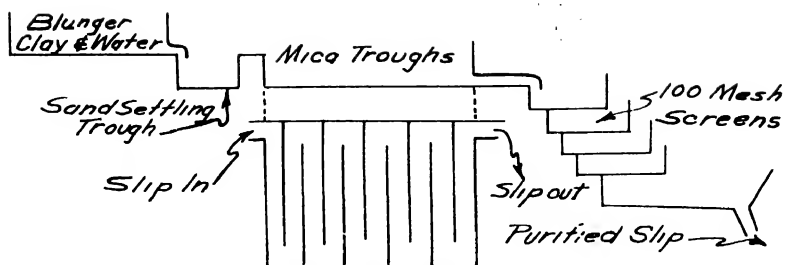


Fig. 29. Clay Washing

Blungers and Agitators. The blunger is designed to rapidly and thoroughly disintegrate clays or blends of clays and other materials, to produce a slip, and to hold it in suspension.

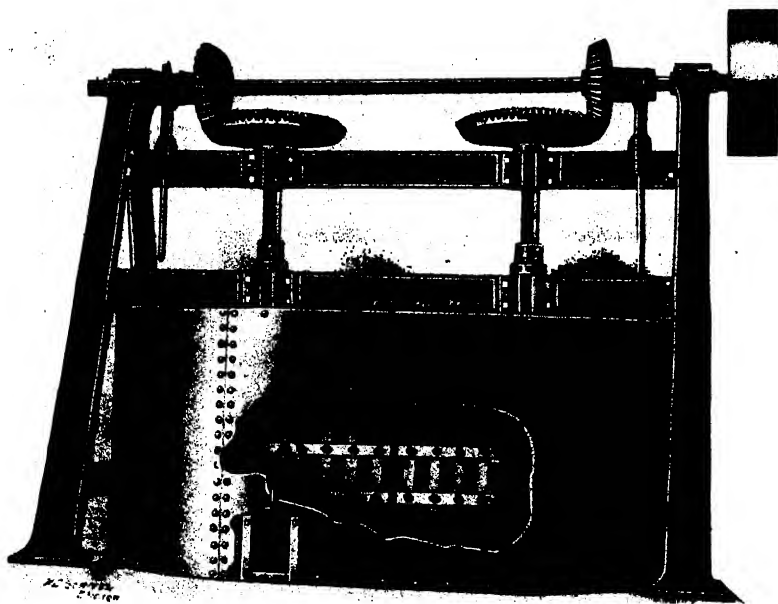


Fig. 30. Double Blunger
(Courtesy Patterson Foundry and Machine Co.)

The blunger (Fig. 30) consists of a large, vertical, cylindrical tank made of steel or wood to hold the slip. One or two vertical shafts, mounted on the framework, extend into the tank and support wood or steel paddles. The double blunger is more efficient than the single blunger, and therefore is more often used in industry. The agitators rotate in opposite directions, thus giving the slip a figure-8 motion. The agitators are rotated at a speed of from 75 to 100 r.p.m. and the capacity of the tank will vary widely. The usual sizes used in the whiteware industries will range from 500 gal. for the single blunger to 1500 gal. for the double blunger.

Blungers are used extensively for mixing and blending body ingredients for whitewares. A predetermined amount of water is usually added first to the blunger, then the clays are added and allowed to become thoroughly mixed with the water. Finally the non-plastics such as flint and feldspar are added and the batch is blunged for a sufficient length of time to produce the desired slip. Since dry clay on "absorbing" and "adsorbing" water tends to become sticky and ball up in lumps, the outside layer of wet, sticky clay will inhibit the water from penetrating to the center of the lump. For this reason, the clay is added to the water before the non-plastics and thoroughly broken up by the action of the blunger.

Following the blunging, the slip is passed through a screen to remove any unmixed lumps or foreign matter, and is then pumped into storage tanks called agitators.

Agitators are simply large tanks of steel or brick, usually set below floor level, that contain a rotating gate which keeps the slip in motion to prevent settling out of the non-plastics. The slip is thus stored in a state of suspension until ready for use.

Chapter 12

SCREENING AND LAWNING

The separation of clay grains and other ceramic raw materials into size ranges is a very important step in their processing. The size of the grains of the materials used in any ceramic body composition will materially affect the physical properties of the fired body. The size and shape of the grains will to a great extent determine the strength, both green and fired, of the body. Large grains will tend to give high porosity and small grains low porosity to the body. Dense refractory bodies of fine-grained material will show a greater tendency to spall under extreme temperature changes than bodies made from coarse-grained materials. Other properties of ceramic bodies affected by grain size of the raw materials are resistance to slag, resistance to freezing and thawing, coefficient of thermal expansion, ability to withstand loads at elevated temperatures, homogeneity of the body with regard to high-temperature chemical reaction, and control of shrinkage. In short, the importance of proper grain sizing cannot be overestimated, as it will be a controlling factor in obtaining almost any desired property in a ceramic body.

Clays may be screened dry or wet. When the materials are dry, the operation is usually referred to as "screening" and when wet as "lawning".

Sizing is the process of dividing mixtures of grains of different sizes into groups whose individual grains are nearly the same size. All of the grains of one group must have passed through a given screen aperture and have failed to pass through some smaller aperture. If the difference in size between openings in the first screen and those in the second screen is relatively small the separation is called close sizing. The screen which just passes all of the material in a given group is called the limiting screen; that which retains all of the particles is the retaining screen. The product from close sizing is said to be short-range. When all of the particles have passed a limiting screen and have been subjected to no further treatment, the product is natural or long-range. Material that fails to pass a given screen is the oversize or plus of that screen; material that passes a given screen is the undersize or minus. In a step sizing operation where a given material is passed through a series of successively smaller screens, the list of apertures of the series of screens is the sieve scale for that particular screening operation. The sieve ratio is the ratio of the aperture of a given screen in a given scale to the aperture of the next

finer screen. The ratio of the combined area of the openings to the total area of the screening surface is the percentage of opening.

The fundamental purpose of screening is to pass all particles below a certain size and to reject all particles above that size. In order to do this perfectly it would be necessary to present each individual particle to an opening, oriented in such a way that its least dimension was perpendicular to the plane of the screen opening and with the verticle axis of the particle in line with the center of the opening. If the particle refused to pass through the opening it should be immediately rejected so as to not interfere with the next particle. Practically this is not possible. In a screening operation the grains are presented to the apertures at a considerable velocity, more or less horizontal to the plane of the opening, oriented randomly, and are continually crowding and interfering with one another. Oversize particles tend to become wedged in the openings and prevent other grains from passing through. True, all oversize particles will fail to pass the screen but many particles that can pass are prevented from doing so and are carried over the screen with the oversize.

The aperture or minimum opening in a wire screen is most accurately expressed in inches or millimeters, but most often as a certain mesh number. Thus a 20-mesh screen means one having 20 openings to the linear inch. This designation of opening size is not definite unless the wire size is known. The wire size will differ for different makes of screens. There are two standards of screen sizes generally used for accurate testing of material size; the U. S. Standard sieve and the Tyler Standard sieve.

U. S. Standard Series. Sieve numbers in this scale run from a 3-in. opening to 400-mesh. In first establishing the scale, the basic opening of 1 mm. was taken. The openings above and below this base opening are related to it by a ratio of 1.1892 or the fourth root of 2.

Tyler Standard Series. This series also extends from an approximately 3-in. opening to 400-mesh. The Tyler series has as its base an opening of .0029 inch, which is the opening in the 200-mesh standard sieve. The openings above and below this bear the ratio of 1.414 or the square root of 2. As can be seen from the table, intermediate sizes are provided for closer sizing.

Woven-wire screens are made with either square or rectangular openings and several different methods of crimping are used, calculated to prolong the life of the screen. Woven-wire screens with elongated openings are used to compensate for loss of effective opening caused when the screen is inclined at an angle. This type will also increase the screening capacity when used with wet or sticky clays and when close precision of sizing is not desired.

Punched-metal screens are available in various metals and alloys and may be punched in various manners (Fig. 31). Punched-metal screens have the following advantages:

U. S. Standard Series

Microns	U. S. Number	Sieve Openings		Tyler Screen Scale Equivalent Mesh
		Millimeters	Inches (Approximate Equivalent)	
5660	No. 3 1/2	5.66	.223	3 1/2
4760	No. 4	4.76	.187	4
4000	No. 5	4.00	.157	5
3360	No. 6	3.36	.132	6
2830	No. 7	2.83	.111	7
2380	No. 8	2.38	.0937	8
2000	No. 10	2.00	.0787	9
1680	No. 12	1.68	.0661	10
1410	No. 14	1.41	.0555	12
1190	No. 16	1.19	.0469	14
1000	No. 18	1.00	.0394	16
840	No. 20	.84	.0331	20
710	No. 25	.71	.0280	24
590	No. 30	.59	.0232	28
500	No. 35	.50	.0197	32
420	No. 40	.42	.0165	35
350	No. 45	.35	.0138	42
297	No. 50	.297	.0117	48
250	No. 60	.250	.0098	60
210	No. 70	.210	.0083	65
177	No. 80	.177	.0070	80
149	No. 100	.149	.0059	100
125	No. 120	.125	.0049	115
105	No. 140	.105	.0041	150
88	No. 170	.088	.0035	170
74	No. 200	.074	.0029	200
62	No. 230	.062	.0024	250
53	No. 270	.053	.0021	270
44	No. 325	.044	.0017	325
37	No. 400	.037	.0015	400

1. They have longer life due to more evenly distributed wear.
2. They have less tendency to blind because of sharp edges of the aperture.
3. On vibrating screens the smoother surface permits a reduction in slope and on a horizontal shaking screen it accelerates the rate of travel.
4. The smooth surface causes less interference with stratification of fine particles in contact with the screen surface, thus promoting efficiency of separation.

Tyler Standard Series

Tyler Standard Screen Scale $\sqrt{2}$ Opening in Inches	For Closer Sizing Ratio $\frac{4}{\sqrt{2}}$ Opening in Inches	Mesh	Diameter of Wire, Decimal of an Inch	U. S. Series Equivalents (Fine Series)	
				MICRON Designa- tion	Number
3	-----	----	.207	-----	-----
2	-----	----	.192	-----	-----
1.5	-----	----	.162	-----	-----
1.050	1.050	----	.148	-----	-----
-----	.883	----	.135	-----	-----
.742	.742	----	.135	-----	-----
-----	.624	----	.120	-----	-----
.525	.525	----	.105	-----	-----
-----	.441	----	.105	-----	-----
.371	.371	----	.092	-----	-----
-----	.312	2 1/2	.088	-----	-----
.263	.263	3	.070	-----	-----
-----	.221	3 1/2	.065	5660	3 1/2
.185	.185	4	.065	4760	4
-----	.156	5	.044	4000	5
.131	.131	6	.036	3360	6
-----	.110	7	.0328	2830	7
.093	.093	8	.032	2380	8
-----	.078	9	.033	2000	10
.065	.065	10	.035	1680	12
-----	.055	12	.028	1410	14
.046	.046	14	.025	1190	16
-----	.0390	16	.0235	1000	18
.0328	.0328	20	.0172	840	20
-----	.0276	24	.0141	710	25
.0232	.0232	28	.0125	590	30
-----	.0195	32	.0118	500	35
.0164	.0164	35	.0122	420	40
-----	.0138	42	.0100	350	45
.0116	.0116	48	.0092	297	50
-----	.0097	60	.0070	250	60
.0082	.0082	65	.0072	210	70
-----	.0069	80	.0056	177	80
.0058	.0058	100	.0042	149	100
-----	.0049	115	.0038	125	120
.0041	.0041	150	.0026	105	140
-----	.0035	170	.0024	88	170
.0029	.0029	200	.0021	74	200
-----	.0024	250	.0016	62	230
.0021	.0021	270	.0016	53	270
-----	.0017	325	.0014	44	325
.0015	.0015	400	.001	37	400

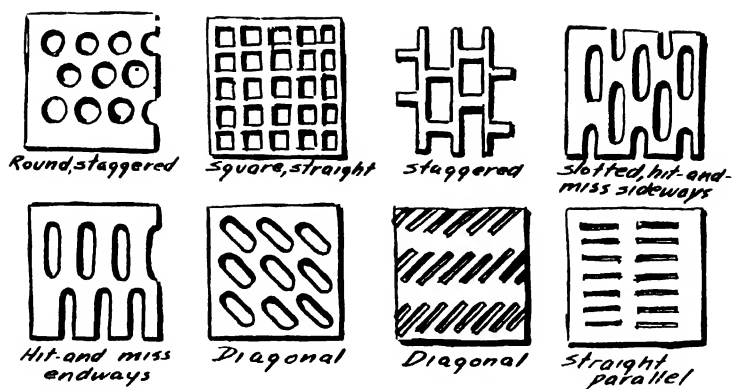


Fig. 31. Types of Punched-plate Screens

In many ceramic industries, especially those producing rough products such as building brick and tile, approximate sizing of raw material is all that is required. For this purpose a stationary, sloping screen is cheap and will do the job sufficiently well. The simplest of this type is the piano-wire screen. It consists of a number of wires stretched taut on a frame and set at an incline. The clay is allowed to flow over the screen, the direction of flow being parallel to the direction of the wires. The screen size of the material is controlled by the width of the setting of the wires. The screen sizing is not close, but all particles over a certain maximum diameter will be removed. Such screens are placed at an incline of 35 to 45 degrees and vary in length from 6 to 14 feet, with a width of about 3 feet. Fig. 32 illustrates different types of mesh used in screening.

The revolving screen or trommel has, to a large extent, been supplanted by the vibrating screen. It consists of a shaft carrying two or more armed spiders, on the outer end of which circular bands are mounted, on which screen cloth or punched-metal plate is stretched. The main shaft is supported by bearings at the two ends and driven by means of a gear and pinion. The screen cloth is usually mounted in sections, and two or three different mesh screens may be mounted on a single trommel if desired, thus obtaining selective screening. Common diameters of the revolving screen (Fig. 33) are 24, 30, 36, 42, 48, and 60 inches; lengths, 4 to 12 feet.

Vibrating Screens are more modern and most widely used. Where close sizing is required, the vibrating screen provides the largest tonnage, but has a higher first cost and is more expensive to maintain than other types. Since vibrating screens give positive motion to the clay particles, they may be set at a lower angle of inclination than stationary screens and require less head room. Vibrating screens may be actuated mechanically or electrically.

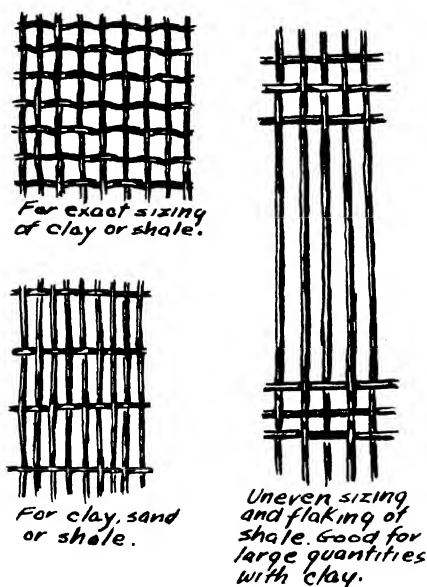


Fig. 32. Screen Mesh

Shaking screens are simply a wooden or metal frame in the form of a shallow rectangular box, two times or more as long as wide, open at one end, with a screen surface stretched tight across the bottom, and so mounted that they can be shaken either manually or mechanically. The material is moved across the screen surface partly by the shaking motion and partly by gravity induced by the slope of the surface. As the load passes over the screen the undersize falls through the screen openings and the oversize is discharged over the end. In order to facilitate the shaking motion the screen is usually hung on four vertical rods or chains at the corners and actuated by an eccentric which produces a substantially straight-line harmonic motion. In order to effectively move the load the screen must have a slope of from 10 to 15 degrees. Sometimes the forward stroke is ended against a bumping block but this results in excessive wear on the screen frame and supports. If the supporting rods are inclined at an angle of about 15 degrees backward from the vertical, the motion of the screen surface will be upward at the end of the forward stroke and sharply downward at the beginning of the backward stroke, with the result that the screen surface will drop away from the material and the load moves forward with a series of jumps.

Speed and length of stroke and slope of screen are the important factors governing the efficiency of a shaking screen. It is desirable

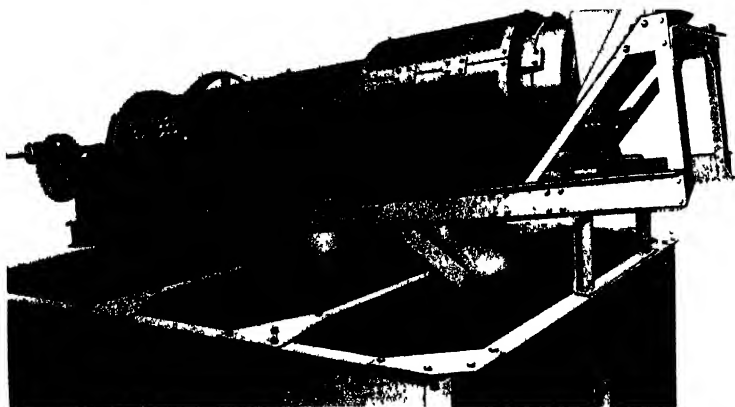


Fig. 33. Revolving Screen
(Courtesy Pioneer Engineering Works)

to produce stratification of the feed as much as possible. That is, if the load passing over the screen surface can be stratified so that the smaller grains are on the bottom in contact with the screen, and the coarser grains are on the top where they do not interfere with particles that can pass the apertures, the efficiency of the screen will be at its maximum. While perfect stratification is not practical, by careful regulation of screening conditions a fair amount of stratification can be attained. If either the speed or length of stroke is too great the material will be thrown violently from the screen surface and stratification will not be effected. If the speed is too slow or length of stroke too short, then there will be too little movement of the material on the screen and the apertures will tend to become plugged. With the proper adjustment of slope, speed, and length of stroke there will be a minimum tendency for the screen to blind and maximum stratification will be attained. Speeds in practice range from about sixty to seventy 9-in. strokes per minute to about eight hundred $\frac{3}{4}$ -in. strokes.

Vibrating screens are essentially similar to shaking screens in shape and size. They differ in that vibrating screens are not shaken but movement of the load over the surface is accomplished by either mechanical or electrical vibration of the screening surface. Sizes, which are stated as deck dimensions, range from $1\frac{1}{2} \times 3$ feet to 6×16 feet and multiple deck screens are available up to six screening surfaces.

Vibrating screens may be divided, fundamentally, into two classes, (a) those in which points on the screening surface reciprocate over substantially rectilinear paths, and (b) those in which the paths are closed, either circular or nearly elliptical in shape. In both cases the path lies in a plane parallel to the sides of the screen box. For

mechanically vibrated screens the vibration is accomplished by cams, eccentrics, gyrators, hammers or a combination of these means.

Particles are moved over the screen surface partly by gravity and partly by the vibration of the screen. The best conditions for particle movement are attained when:

1. There is rapid movement of the load over the screen surface. This governs the capacity of the screen but not its efficiency.
2. There is more or less continuous contact of the material with the surface. This allows each particle to be presented to the maximum number of openings.
3. There is continuous turnover. Turnover is the bouncing of a particle to change its orientation when presented to different openings so that it will have every chance of passing through one of them.
4. There is ejection of particles that fail to pass a given opening and become wedged therein. This prevents blinding and gives other particles access to that opening.

Practically, it is not possible to have an ideal screen operation that will satisfy all four of the above conditions. Continuous contact and turnover, for example, are in direct opposition. The operator must, therefore, adjust all four conditions in such relationship to each other, that he obtains the most efficient operation for a given job, using a given screen, screening a given material.

Rapid movement over the screen surface may be attained by increased slope or rapid vibration or a combination of both. The speed of vibration and slope should not be so great as to cause the material to bound across the surface of the screen, and thus, very materially shorten the effective length of the screen.

Continuous contact is obtained by decreasing the slope and increasing the load on the screen. Both tend to decrease the length of jumps of the particles for a given intensity of vibration. Too little slope or too great a load lessens the efficiency of the screen and increases its tendency to blind.

Turnover is assisted by the rough surface of the screen which offers a certain amount of opposition to the particles flowing over it. It is mainly accomplished by counterflow, or the closed-path motion of the screen, when the upper portion of the vibratory path is directed toward the feed end of the screen.

Ejection is best attained by impact on the screen at the time it reaches the end of its upward stroke. The elliptical path of the screen surface also causes ejection of the particles from openings they fail to pass.

Two types of screens that will serve as examples of the mechanically vibrated screen are (a) the Leahy Vibrating Screen, Figs. 34 and 35; and (b) the Universal Vibrating Screen, Figs. 36 and 37.

Magnetically Vibrated Screens are activated by solenoids. They are used a great deal in the whitewares industries for fine sizing, wet or

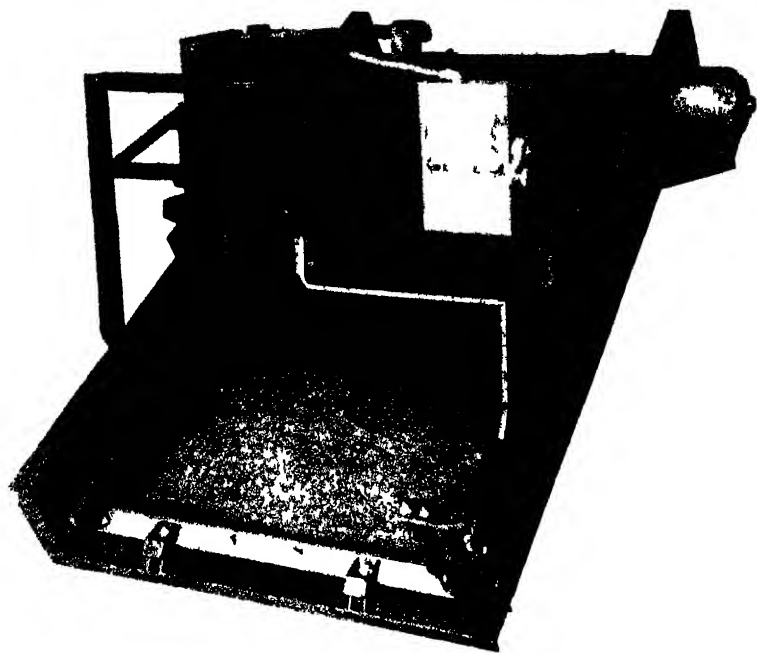


Fig. 34. Leaky Screen
(Courtesy The Deister Concentrator Co.)

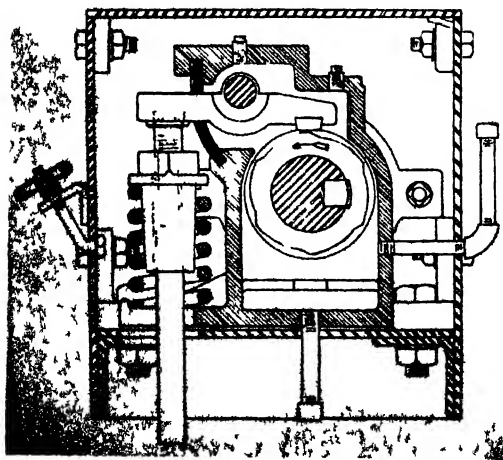


Fig. 35 Cross Section of Leaky Vibrator Mechanism
(Courtesy The Deister Concentrator Co.)

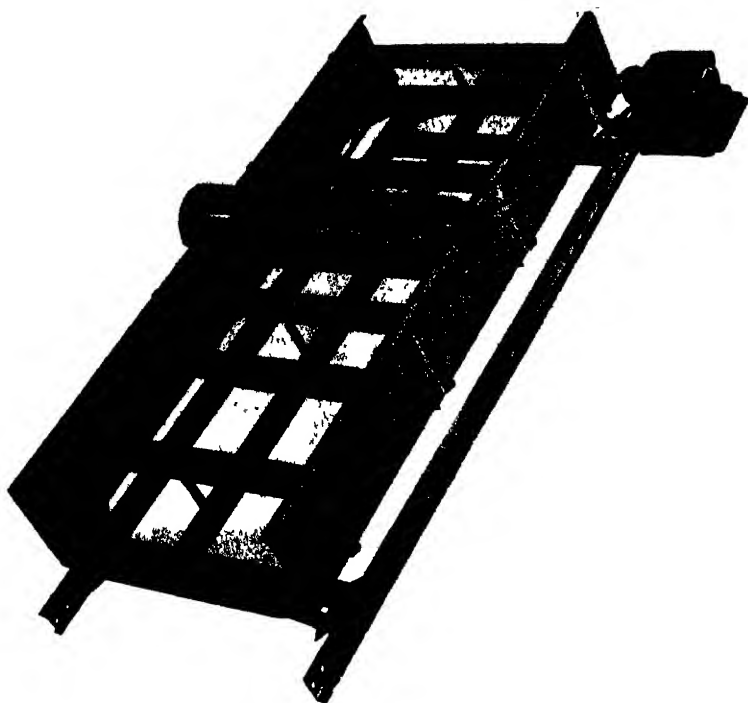


Fig. 36. Universal Screen
(Courtesy Universal Vibrating Screen Co.)

dry. Their advantage, compared with mechanically vibrated screens, lies in the absence of rotating elements requiring lubrication and protection. Nearly all magnetically vibrated screens require special generating or modifying equipment to convert the customary available power supply into current appropriate for the screen.

The Hum-mer Screen (Fig. 38) consists of a screen cloth stretched cross wise and attached to the side walls of a stationary box. Vibration is applied at the center of the screen, and normal thereto, and is transmitted lengthwise by straps bolted through the cloth above and below, along its center line. The vibrator is mounted on a bridge crosswise of the box. The electromagnet "2" is firmly bolted to the cover of the casing. The armature "4" is maintained in central position by a ribbon spring and is restrained in both vertical directions by helical compression springs. Amplitude of vibration is governed by pressure applied through the hand wheel "1", and is adjusted to allow the ends of the armature to strike the blocks "3" with such impact as may be required



Fig. 37. Universal Screen Vibrating Mechanism
(Courtesy Universal Vibrating Screen Co.)

for effective screening. Vibrations and impacts are transmitted to the screen "6" through the connecting rod "5". Standard screen widths are 3 and 4 feet, and the usual inclination 33 degrees. Frequencies available are 900, 1800, and 3600 v.p.m. Amplitudes are from $1/32$ to $1/8$ inch in the vibrator, amplified somewhat by the screen.

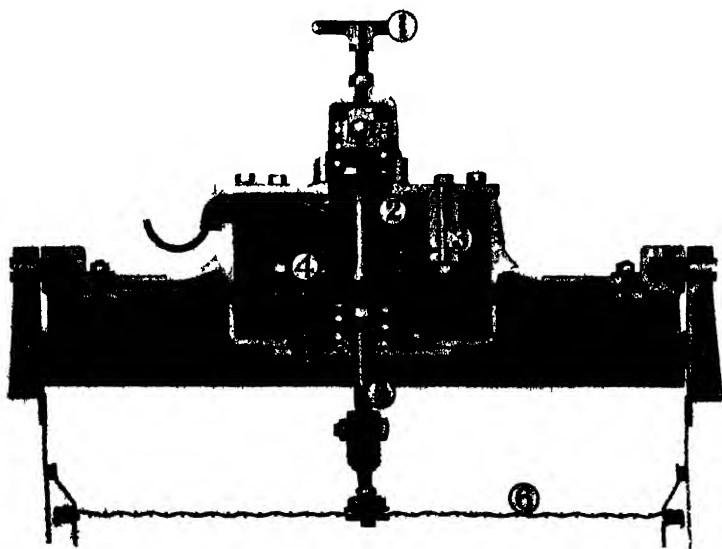


Fig. 38. Hum-mer Vibrator
(Courtesy The W. S. Tyler Co.)

The purpose of vibration in screening is to assist the flow of material over an inclined screen, and to jump particles over the obstructions formed by the uneven screen surface. The intensity of vibration, therefore, must be sufficient to accomplish this purpose. If the slope of the screen is slight, the intensity of vibration must be greater than would be necessary with a steeper inclination. The vibratory impulses must throw the particles clear of the surface, and the direction and speed of the particles must be such that, when they again fall onto the surface, they are nearer the discharge end than when they left. The intensity must be sufficient to dislodge particles that have become caught in the apertures. Therefore the intensity must be greater (a) for larger particles than smaller ones, (b) for heavier loads than lighter ones, (c) for lower slopes than greater, and (d) for screens and material that have a greater tendency to blind.

Too great an intensity of vibration prevents good stratification, tends to jump near-mesh particles out of apertures before they have had a full opportunity to pass through, increases the length of particle jumps so that the particles are not presented to a sufficient number of openings thereby reducing the effective length of the screen, and causes undue wear on the screen. Under-intensity increases the tendency of the screen to blind and reduces the capacity. Intensity can be controlled through speed and amplitude. With magnetic vibrators the speed is not variable but the amplitude can be readily changed. In general, high speed and a stroke short enough to prevent blinding will give the highest efficiency for finer screening; in coarse screening, good efficiency can be obtained at any stroke that will move the bed.

The slope of the screen in conjunction with intensity will govern the rate of flow, and rate of flow with rate of feed determines the thickness of the load on the screen. The proper slope will vary with the material being treated. Flatter slopes tend to cause thicker beds, heavier loads, more blinding, screen wear, and less efficiency. Too great a slope means more missed apertures with a consequent loss in efficiency.

The capacity of a screen will be affected by (1) percentage of opening, (2) shape of opening, (3) distribution of feed across the deck, and (4) intensity of vibration.

The proper suspension of vibrating screens is an important factor in their efficiency and cost of maintenance. Fig. 39 illustrates four correct methods and one incorrect. Suspending rods should never be rigidly supported to a beam or the proper vibration of the screen will be interfered with and excessive rack and vibration on the screen will result.

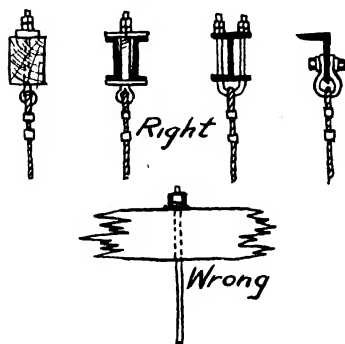


Fig. 39. Methods of Hanging Vibrating Screens

Chapter 13

CLASSIFICATION WITH WATER

Classification with water is an operation whereby aggregates of mixed grain sizes are separated, using the principle of sedimentation. Water is the most commonly used liquid medium and it may be either in motion or substantially at rest. Wet classification is used for removing sand and mica from raw kaolins in settling tanks or mica troughs, as previously mentioned.

Before considering the various types of equipment used for wet classification, it will be well to review the general laws of wet classification. These are given by Taggart* as:

1. The relative settling velocities of particles of the same specific gravity and the same shape in a given liquid are dependent upon the sizes of the particles, the larger (and heavier) settling the more rapidly.
2. If particles are of the same size and shape but of different specific gravities, they settle at different rates proportional to their specific gravities.
3. If particles are of the same weight but of different shapes, their settling velocities will probably differ; the particles most nearly spherical will fall most rapidly; those most tabular, most slowly.
4. Resistance to fall in a given liquid is dependent upon the velocity of the falling particle. Resistance varies directly as the velocity when the latter is low, as the square of the velocity when the velocity is high, and as some intermediate power or powers in the transition range.
5. Velocity of fall in a given liquid, all other things being equal, varies as the squares of the diameters of the particles when these are very small, as the $1/2$ -power of the diameters when the particles are relatively large, and as an intermediate power or powers in the transition range.
6. Resistance to fall increases with the density of the liquid.
7. Resistance to fall increases with the viscosity of the liquid. This increase is relatively greater the smaller the particle.

Classifiers may be grouped into two general types, (a) horizontal-current classifiers and (b) vertical-current classifiers. Horizontal-current classifiers are characterized by some type of mechanical agitator to keep the pulp in a sufficient state of agitation that only the

* Taggart - Handbook of Mineral Dressing, Sec. 8

heavier particles will settle out. The current flow is horizontal; the finer or lighter particles being transported and collected at the discharge end of the apparatus, while the heavier and coarser particles settle and are removed either continuously or periodically.

Vertical-current classifiers are characterized by the utilization of a rising current, the velocity of which is controllable. The finer particles are carried out at the overflow and the coarser particles settle to a discharge opening at the bottom of the apparatus.

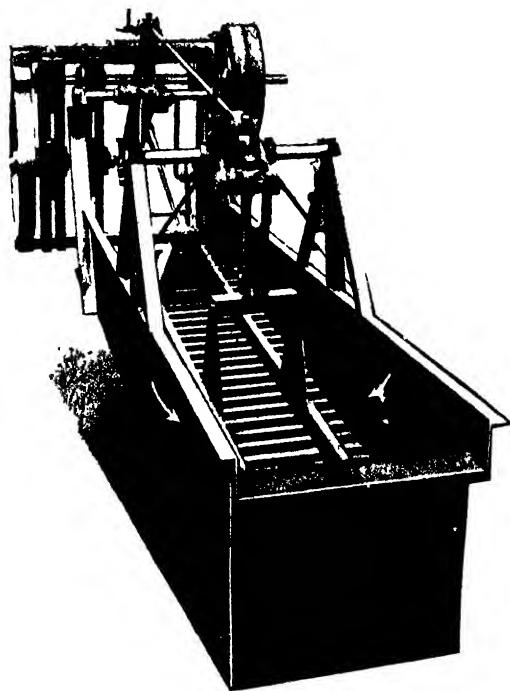


Fig. 40. Rake Classifier
(Courtesy Denver Equipment Co.)

The rake classifier (Fig. 40) comprises a tank, one or more rakes, and a mechanism for actuating the rakes. The tank has parallel vertical sides, a vertical wall at the overflow end, and a sloping bottom of such length that its upper end rises above the level of the top of the lower end wall. The rakes consist of a number of parallel blades set perpendicular to the tank bottom.

Feed is introduced toward the lower end of the tank and flows over a distributing apron toward the high end. Water is continuously added

to the apparatus by means of a spray and overflows continuously at the lower end of the tank. When the feed in the form of pulp or slurry is introduced, the coarser and heavier particles will tend to settle to the bottom and the finer and lighter particles will be carried off by the overflow. It is the purpose of the rakes to remove the settled particles. The rakes are actuated by a system of cranks and eccentrics so that they describe a roughly rectilinear path, with long sides parallel to the bottom of the tank. On the forward stroke, which is toward the high end of the tank, the blades are almost scraping along the bottom of the tank; on the return stroke the blades are lifted above the tank bottom. Thus the settled material is continuously dragged by the rakes toward the high end of the tank and above the water line, where it is finally discharged through an opening in the bottom of the tank.

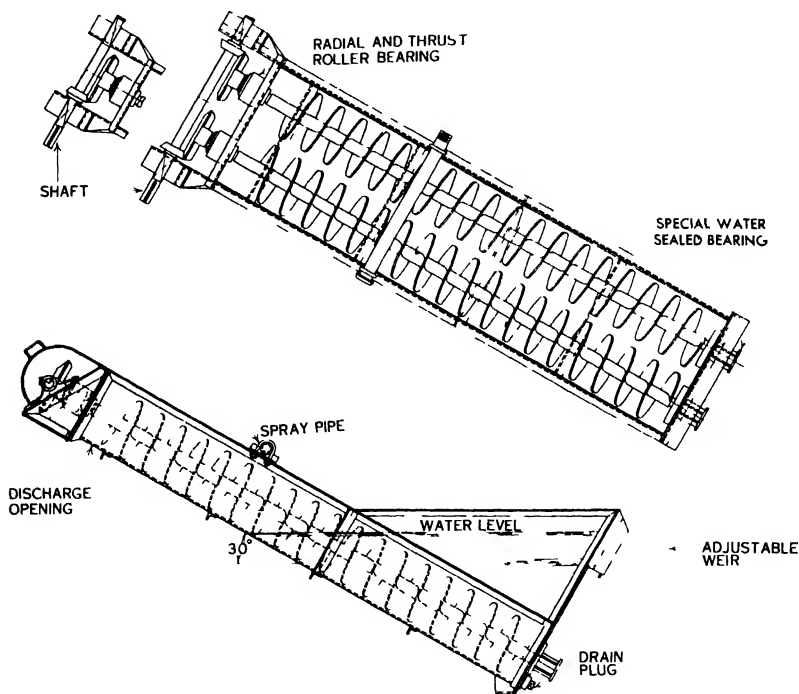


Fig. 41. Spiral Classifier

The Spiral classifier (Fig. 41) is essentially the same in principle as the rake classifier, except that in place of a series of rakes the Spiral classifier has one or two spirals mounted on a through shaft

substantially parallel to the tank bottom. The tank bottom is rounded and the spirals revolve so as to carry the sedimented material upward toward the high end of the tank, where it is discharged.

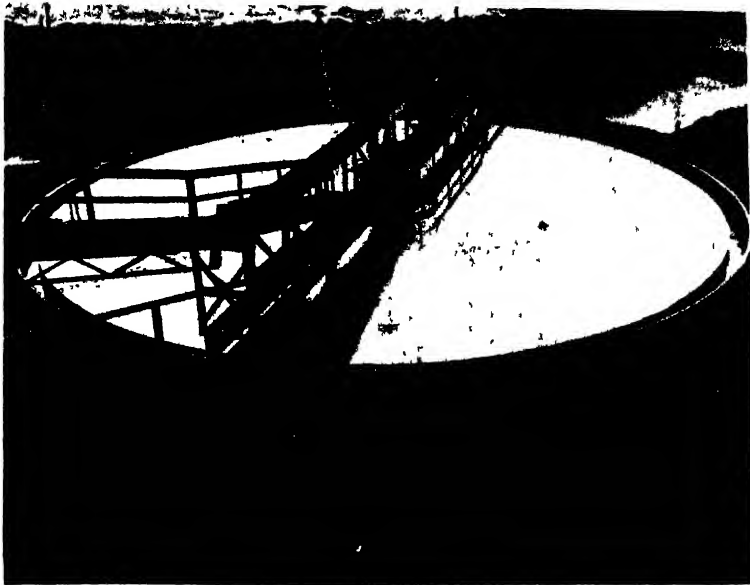


Fig. 42. Hydro-Classifier
(Courtesy Hardinge Co.)

The Hydro-classifier (Figs. 42 and 43) consists of a shallow tank with an obtusely conical bottom and a rim adjustable in height. Pulp is introduced into the bowl along with a continuous flow of water, and separation of particles is effected by sedimentation. The slurry is kept in a state of agitation by a series of rakes carried on a center column, which is suspended from a gear drive mechanism mounted on a framework. The rakes rotate and slowly drag the settled material to the center of the conical bottom, where it is discharged into a spiral screw-conveyor. The rim of the bowl, which acts as an overflow weir, is adjustable vertically through a range of 100% of minimum and thus the depth of liquid through which the particles must settle is controllable.

In some cases the hydro- and rake classifiers are used in conjunction with one another, the two arranged so that the center well discharge of the bowl classifier feeds directly into the lower end of a rake classifier. In this way an additional washing is given the material and fine material not completely separated from the coarse by the bowl classifier will be carried out with the overflow from the rake classifier.

The above classifiers are all of the horizontal-current type and are used in the ceramic industry chiefly for purifying kaolins and other

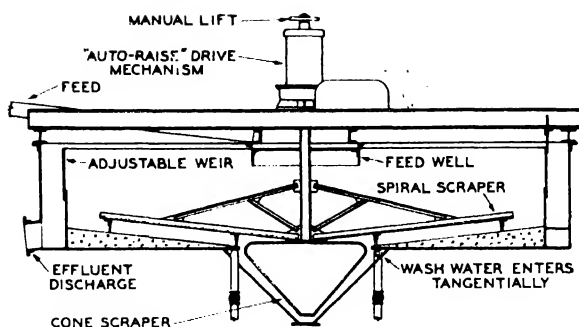


Fig. 43. Hydro-Classifier
(Courtesy Hardinge Co.)

high-grade clays. They may also be used for washing impurities from silica sands, feldspars, carborundum and other ceramic raw materials. While they do effect a certain amount of size classification, that is not their primary purpose and they should not be used for that purpose, except where size classification is incidental to the separation of different materials.

Vertical-current Classifiers. This type of classifier is not used extensively in the treatment of clays but may, on occasion, be found to be the most economical method for separating grain sizes of non-plastic ceramic materials such as silicon carbide and other abrasive

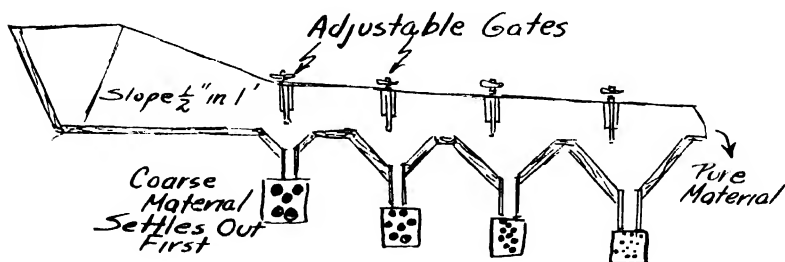


Fig. 44. Richards Vortex Classifier

The Richards launder-type vortex classifier (Fig. 44) will serve as an example of the principles involved in vertical-current classifiers. It consists of a trough of increasing width from the feed end to the discharge end, provided with pockets above the sorting columns of sufficient size and depth to effect a rough segregation of the feed to the

column, sending along to the next pocket most of the material that could not settle in the sorting column proper and holding back material that might settle in the column long enough to give it an opportunity to do so.

Since the width of the trough increases toward the discharge end, and since the pockets are made longer and deeper the nearer they are to the discharge end, therefore the cross-sectional area of each succeeding pocket is greater toward the discharge end. This means that the velocity of flow of the liquid decreases as it approaches the discharge end and that heavier and coarser particles will settle out in the first pocket and successively finer particles in each succeeding pocket.

To the bottom of each sorting column is fixed a vortex fitting (Fig. 45). Water entering the tangential inlet pipe takes on a swirling motion around a vertical axis and retains this motion in rising through the sorting column. The vertical flow of water carries the fines upward, or prevents them from settling at all, until they are carried by horizontal flow of water into the next pocket; the coarse material is drained off at the bottom of the vortex fitting. The velocity of the water flowing through the vortex fitting can be regulated and adjusted until the desired size of product is obtained.

Above each pocket is fixed an adjustable gate which may be raised or lowered to regulate the flow of water at any desired point. The finest particles of all overflow at one end of the trough, but if the classifier is made with a sufficient number of pockets practically no solids will be carried over with the overflow.

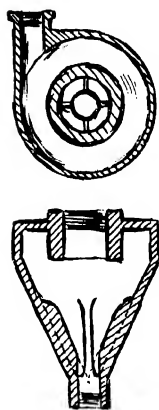


Fig. 45. Richards
Vortex Fitting

Chapter 14

MAGNETIC SEPARATION

Many impurities in clays and other ceramic materials are weakly to strongly magnetic and can best be removed by magnetic separators. Such separators are designed to remove such magnetic minerals as magnetite, ilmenite and sometimes mica. Often, during the various treatments given to clays, they will become contaminated with tramp iron such as nails, bolts or bits of machinery, and it is advisable to pass the material through a magnetic separator to insure the removal of all such free iron before the clay is used in preparation of the body. Magnetic separators may be used with either wet or dry materials.

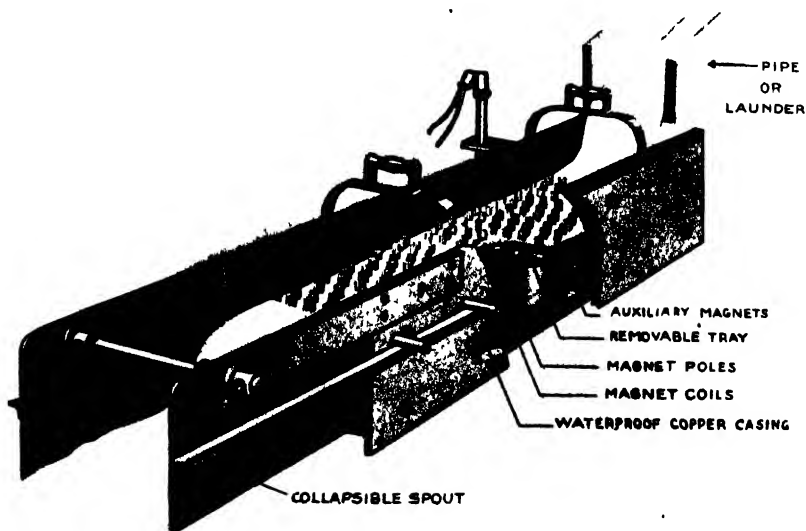


Fig. 46. Dings Magnetic Separator
(Courtesy Dings Magnetic Separator Co.)

The Dings magnetic separator (Fig. 46) consists of a trough having a removable deck or tray over which the slip is allowed to flow. The removable tray contains a series of auxiliary magnets in the form of

iron pole pieces, in staggered rows, which are actuated by a series of strong electro-magnets placed directly beneath the tray. As the slip flows over the separator, it comes in contact with the numerous auxiliary magnets and magnetic impurities will be attracted by, and cling to, the magnetized pole pieces. Periodically the current must be cut off and the tray removed for cleaning.

The Frantz Ferro-filter (Fig. 47) is a type of magnetic separator used quite extensively in the preparation of whiteware bodies. It contains a series of screens, made of iron, placed in the line of flow of

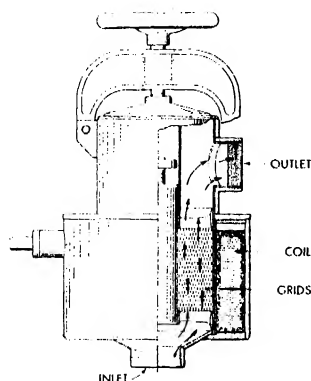


Fig. 47. Ferro Filter
(Courtesy S. G. Frantz Co.)

the slip, and magnetized by a cylindrical coil. The magnetized screens expose a large surface to the slip and efficiently remove a large percentage of the iron bearing particles. The magnetic screens must be cleaned periodically to remove the particles that adhere to them. This is done by turning off the current and running clear water through the separators. For most pottery slips the magnets are cleaned two or three times a day when running continuously.

Sizes are rated to handle from 50 to 2000 gal. per hr. with different screen openings; lineal feet of screen collecting edges range from 260 to 5000 feet.

Dry magnetic separation is most simply accomplished by means of a magnetic pulley over which an endless belt is run (Fig. 48).

Magnetic-pulley separators are made up of a belt conveyor with a magnetic head pulley, a feeder to deliver a thin layer on the carrying portion of the belt, and a divided receiving chute to take the two products. The magnetic pulley consists of a number of circular, horseshoe permanent or electromagnets, the whole assembled on a common shaft. As the ore passes over the pulley, the non-magnetic portion discharges by gravity, while the magnetic portion is held to the belt by the magnetism of the pulley until it passes out of the field of magnetic force.

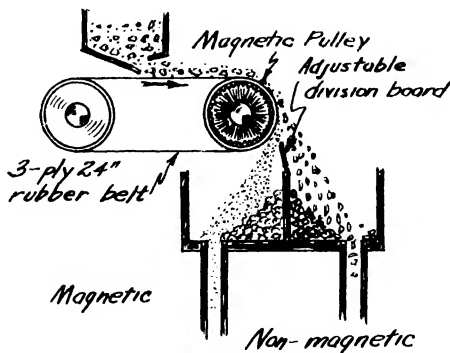


Fig. 48. Magnetic Pulley

A similar type of magnetic separator uses a permanent electro-magnet and two conveyor belts set at right angles to one another (Fig. 49). An ordinary belt conveyor is set with a short cross-conveyor at right angles to it and placed very close to its carrying surface.

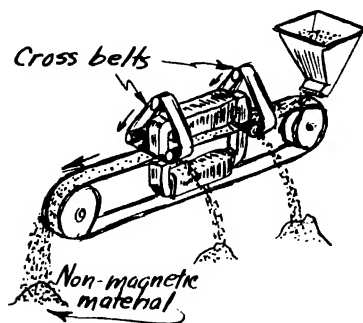


Fig. 49. Magnetic Cross Belt

The cross-conveyor passes under an electromagnetic coil so that as the material on the main conveyor passes under the cross-conveyor belt, magnetic particles are picked up by it and carried away to be dropped off when the cross-belt passes beyond the field of magnetism. The non-magnetic material is carried to the end of the main conveyor belt and deposited in a suitable container.

Induced-roll Separator (Fig. 50) consists of a number of high-intensity drums in series. Transversely laminated rolls "A", made of alternate sheets of a

highly permeable material such as soft iron and of a non-magnetic material such as zinc, are located between the poles "C" of an electro-magnet and the induced poles "B" of a bridge-bar or keeper, and are rotated in the directions indicated. The strength of the field can be varied over a wide range of intensity and the number of rotors can be so arranged as to graduate from a low field intensity to a high field intensity, from the order of 5000 maxwells to 125,000 maxwells per sq. inch. The laminated rotor is essential to obtain converging lines of force from the pole to the rotor.

In the operation of the Exolon High Intensity Induction Magnetic Separator, the granular material is fed over the whole length of the 30-in. top rotor by a gravity feed hopper or a vibrator feed hopper. The magnetic field and the converging action of this field make the magnetized material cling to the rotor longer than the non-magnetic, and it falls in a separate trajectory from the non-magnetic. A knife edge can readily be inserted between these two trajectories and an effective separation is obtained. Thus the readily susceptible material is removed from the stream and the remainder is fed by a chute to the second rotor. Again the magnetically susceptible material is removed and the remainder is fed to a third rotor. Depending on the characteristics of the material to be separated, three to eight rotors are required.

The usual capacity is rated as 67 pounds per rotor inch or 2000 pounds per hour for materials of a density similar to sand or quartz, at a rotor speed of 100 to 110 r.p.m.

The strength of the fields is varied according to the susceptibility of the minerals to be separated. Ilmenite and rutile may be separated

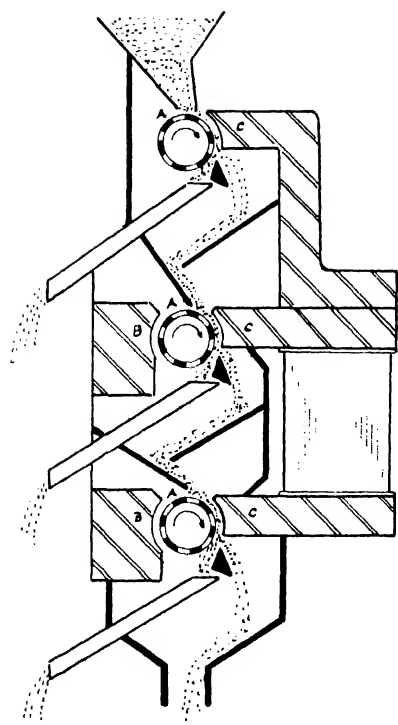


Fig. 50. Induced-Roll Separator

from zircon or a zircon sand with field strengths of 5000 maxwells on the first rotor, 40,000 maxwells on the second and 45,000 maxwells on the third. On the other hand, to clean a feldspar of biotite, mica, tourmaline and muscovite mica, garnet, etc., requires 5000 maxwells on the first rotor, 80,000 maxwells on the second and 85,000 maxwells on the third.

The following table gives the field density in thousands of maxwells per sq. in. for some of the more common minerals.

The high intensity induction magnetic separator has been found useful in the beneficiation of such ceramic raw materials as borax ores, feldspars, nepheline syenite, titanium-bearing sands and ores, certain clays, mullite, kyanite, silica sand, quartz, cryolite, barite, fluorite, zircon and zirconium oxide, and bauxite.

Flux Density in Maxwells
per sq. inch
Thousands

Mineral

5	Ilmenite, Magnetite
5-10	Ilmenite, Pyrrhotite
10-15	Garnet, Hematite, Ilmenite
15-25	Emery, Garnet, Ilmenite
25-45	Franklinite, Garnet, Ilmenite, Limonite, Pyrolusite, Rutile
45-65	Arsenopyrite, Biotite, Chalcopryrite, Chromite, Franklinite, Manganite, Pyrolusite, Rutile
65-85	Beryl, Carnotite, Biotite, Cassit- erite, Chromite, Cinnabar, Corun- dum, Hornblende, Monazite, Mus- covite, Cryolite, Olivine, Rutile, Serpentine, Siderite, Sphalerite, Wolframite, Tourmaline

Chapter 15

CRUSHING AND GRINDING

One of the first steps in beneficiation of clays and other ceramic raw materials is crushing and grinding. Clays will vary in hardness from soft, friable, lumpy material to the almost rock-like, hard, flint fire clay. Shales lie, in hardness, somewhere in between the surface clays and flint fire clays and vary in themselves from soft to very hard. Quartzites, feldspars and nepheline syenites are hard and tend to shatter when crushed. Each type of material presents its own particular crushing problem and the most suitable type of crushing machine must be carefully selected for the material to be crushed.

Crushing and grinding, or the breaking down of large size lumps of material into successively smaller grain sizes is called "comminution". It is usually a stage process, utilizing in successive steps machines especially suitable for reduction in each size range. The breaking down of crude lumps as mined or quarried to about 14-mesh size is called crushing and further reduction in size to 20-mesh or finer is called grinding. The various stages of crushing may be referred to as primary crushing, secondary crushing and so on.

Many clays, as taken from the ground, are already fine enough that they require no primary crushing. This is generally the case with surface clays used for making structural clay products. In this case, secondary crushing is all that is required, since fine grinding of clays is not necessary for making building brick and tile. Fine grinding is employed mostly in the case of the high-grade clays such as ball clays, kaolins, and fire clays. Often, for ball clays and flint fire clays, it is necessary to employ several steps of comminution from primary crushing to very fine grinding.

Crushing is a mechanical operation in which a sufficient force is applied to solid particles in such directions that failure of the bonding forces in the particles is brought about. Crushing machines, therefore, must be so designed that they exert either pushes or pulls on individual particles and the solid particles must be so introduced and maintained in the force zone that the forces available can be applied to them.

These forces (pushes or pulls) may be applied to the particles to be crushed in various ways. Methods of applying the forces will determine the design and working principle of the machine exerting the force.

Principles of comminution which influence the design of crushing machinery are:

1. **Compression.** A uniformly increasing load is applied directly to the particle to be crushed until failure of the particle takes place.

2. **Impact.** The load or force is applied with a certain velocity, striking the particle and causing it to fail from the force of the blow.
3. **Attrition.** The abrasion or grinding force applied to a particle between two hard surfaces.
4. **Beam action.** The breaking of a particle transversely by means of a force applied between two supports which exert a counter force.
5. **Roll action.** The particle is pinched and broken between two cylindrical rolls revolving toward each other. This also involves some compression.

With few exceptions, all crushers taking course feeds apply pressure gradually to particles which take the load as simple beams or short columns. Three general types of mechanism are employed:

1. **Reciprocating pressure breakers** in which the crushing surfaces alternately approach and withdraw from each other:
 - a. Jaw crushers
 - b. Gyratory crushers
 - c. Cone crushers
 - d. Gyrosphere crushers
2. **Continuous pressure breakers** in which, in the crushing zone, there is a continuous approach of the crushing surfaces to a substantially fixed predetermined minimum spacing:
 - a. Roll crushers
 - b. Single roll crushers
 - c. Ball mills
 - d. Rod mills
 - e. Dry pan
3. **Impact crushers** in which the particles are repeatedly struck by hammers revolving at high speed, or by falling weights:
 - a. Hammer mills
 - b. Ball mills
 - c. Rod mills

A crushing machine must not only be designed to crush the material, but must also provide a means for continuous presentation of the material to the crushing surfaces and continuous discharge of the crushed material. Gravity is the usual agent employed for presentation of the particles to be crushed, and gravity or gravity aided by the carrying force of air or water or by the mechanical impulse of the crushing surfaces are the usual means of discharge.

Machinery for reducing the size of materials may be classified as follows:

<u>Primary Crushers</u>	<u>Secondary Crushers</u>	<u>Intermediate Crushers</u>	<u>Fine-grinding Mills or Pulverizers</u>
1. Gyratory	1. Crushing rolls	1. Rod mill	1. Pebble mill
2. Jaw	2. Single-roll crusher	2. Ball mill	2. Ball mill
	3. Hammer mill	3. Dry pan	3. Tube mill
	4. Rotary crusher		4. Ring-roll mill
	5. Squirrel-cage disintegrator		5. Buhrstone mill
	6. Gyratory for fine reduction		
	7. Jaw crushers for fine reduction		

Size of product

3-in.	1, 1/2, 1/4-in to 10-mesh	10 to 20 mesh	100, 200, 325-mesh
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Jaw crushers are pressure breakers of the reciprocating type. They consist of two crushing surfaces, one fixed and one movable, set at an angle so that there is a relatively wide opening at the top and small opening at the bottom. By mechanical means the movable surface is caused to approach and recede alternately from the fixed surface. There are two types: the Blake, which has the movable jaw pivoted at the top, and the Dodge, which has the movable jaw pivoted at the bottom.

The best known type is the Blake (Fig. 51) which consists of a main frame carrying a movable jaw and a fixed jaw; the movable jaw pivoted at the top. The movable jaw is caused to swing toward and away from the fixed jaw by toggles and pitman actuated by an eccentric connected to the drive shaft. To one end of the drive shaft is connected the drive pulley and to the other end a fly wheel. Adjustment of the discharge opening, to allow for jaw plate wear, is made by raising or lowering an adjusting block against which the rear toggle is seated.

The size of the opening at the top of the crushing chamber determine the size of rock that the crusher will receive. The maximum size of rock that the crusher will handle efficiently will be approximately two inches smaller than the opening between the jaws. The production of the crusher is directly related to the width of the jaws. Other conditions being equal, a crusher with a 36 inch wide opening will crush 50 percent more than a crusher with a 24 inch wide opening.

There are many factors to consider in selecting the size of a jaw crusher for a particular job. The most important are (a) the jaw

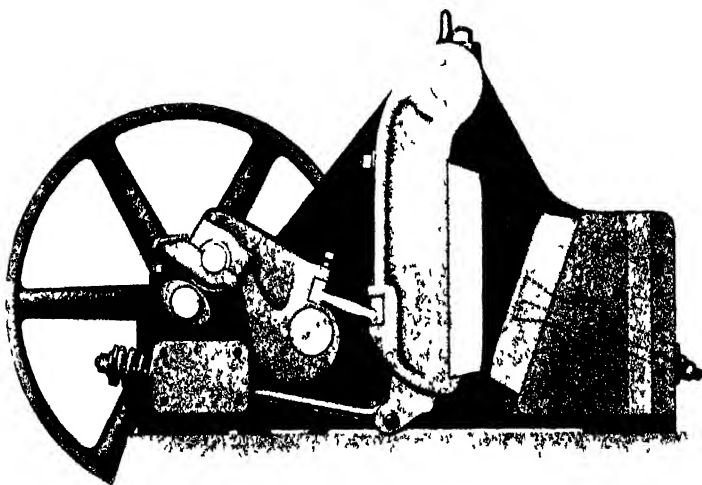


Fig. 51. Jaw Crusher
(Courtesy Sturtevant Mill Co.)

opening, (b) the capacity desired, and (c) the investment. The jaw opening determines the size of rock that can be fed into the crusher and also the capacity of the crusher. The top opening limits the size of feed, the bottom opening the size of product. The ratio of reduction of any crusher is the ratio between the size of the feed and size of the final crushed product. The capacity of the crusher depends upon the reduction ratio, the smaller the ratio the higher the capacity. Capacity is also influenced by the nature and type of rock. Some rocks are brittle and shatter, others are tough and break slowly.

Jaw plates are made in two general shapes. Formerly all jaw plates were made with a flat surface provided with longitudinal corrugations in the form of straight lines. Later, jaw crushers were made with longitudinal corrugations in the form of a convex curve on the swing

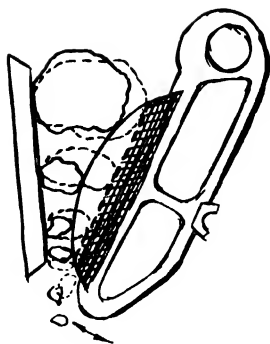


Fig. 52. Comparison of Reductions with Straight and Curved Jaw Plates

jaw, and recently some manufacturers are offering a crusher with a convex plate for both movable and fixed jaw. The effect of the curvature on the efficiency of the machine is shown in Fig. 52. The theoretical result of this difference in shape of jaw face is shown in Fig. 53. A piece of rock which just seats along the line "1" with the movable jaw in closed position will just seat along line "2" when the jaw is in open position, and the vertical distance from "1" to "2" represents its advance downward for this movement. If the particle, now seated at "2", broke on the next forward stroke so that it remained at "2", it would advance to "3" when the jaw again opened. Thus with each complete cycle of the swing jaw the particle would be further crushed and advance to "4", "5", "6", "7", and "8" where it would discharge from the crusher. It can be noted from the

figure that with the straight jaw, the areas between positions "1" to "8" decrease downward, and, therefore, the material in progressive zones will have progressively less space. This means that there will be a progressively increasing tendency for the crusher to choke or become clogged and this tendency will be greatest at the throat. With the curved plate, the minimum area occurs well above the throat, and

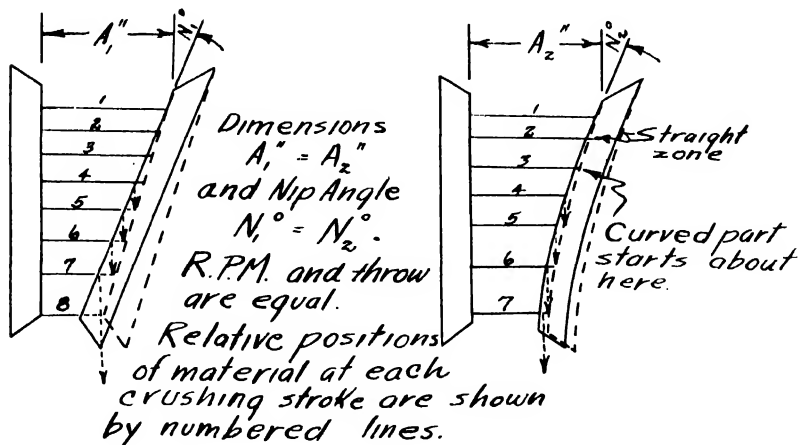


Fig. 53. Comparison of Size Zones with Straight and Curved Jaw Plates

the larger particles have room to spread out as they progress, thus permitting not only increasingly free movements among themselves but also providing for an easier passage of the fine material between the large particles.

Capacities and data on the Blake jaw crusher are given in the following table:

No. of Crusher	Size of jaw opening (in.)	Capacity in tons/hr. size of product in inches					Jaw motion (in.)	Horsepower required	R.P.M.
		1	1-1/2	2	3	4			
2	10 x 7	2-1/2	4	5		A	5/8	7	250-275
		5	8	11		B			
4	20 x 10		10	15	20	A	11/16	15	250-275
			21	28	42	B			
6	30 x 18			38	45	A	11/16	40	250-275
			30	40	60	72	B		

A = Straight jaw plates

B = Non-choking jaw plates

The angle of nip in a jaw crusher is the angle formed by the jaw faces (Fig. 53). The usual range is from 18 to 24 degrees at the open setting for straight jaw machines. The measurement is made at open setting because the nip angle increases as the jaw moves forward and if the angle is too large with the jaws open, this unfavorable condition becomes worse as the jaws close. The critical angle of nip is that angle at which the component forces tending to throw the particle out of the machine are just equal to the component forces tending to hold it in. This is the angle at which the most efficient crushing takes place.

The Dodge Jaw Crusher is similar to the Blake except that the movable jaw is pivoted at the bottom. The swing jaw, being thus pivoted at the bottom, must do its heaviest work at a point on the working end of the lever farthest from the fulcrum and is not economical in the use of power. There is very little movement at the throat and therefore the capacity is low and the tendency to choke is great. There is a further disadvantage in that the machine has difficulty in nipping material and lumps tend to fly out of the jaws.

The gyratory crusher (Fig. 54) is a reciprocating, pressure-type breaker. The upper portion of the shell is in the form of a frustum of an inverted cone and is lined on the inside with breaker plates which act as the fixed crushing surface. Suspended symmetrically on the vertical axis of the fixed crushing surface is a movable crushing surface in the shape of a conical frustum in erect position. The movable crushing cone gyrates and at the same time is free to rotate around its own axis slowly while the crusher is working. The material to be broken is fed into the down-ward converging annular space between these two

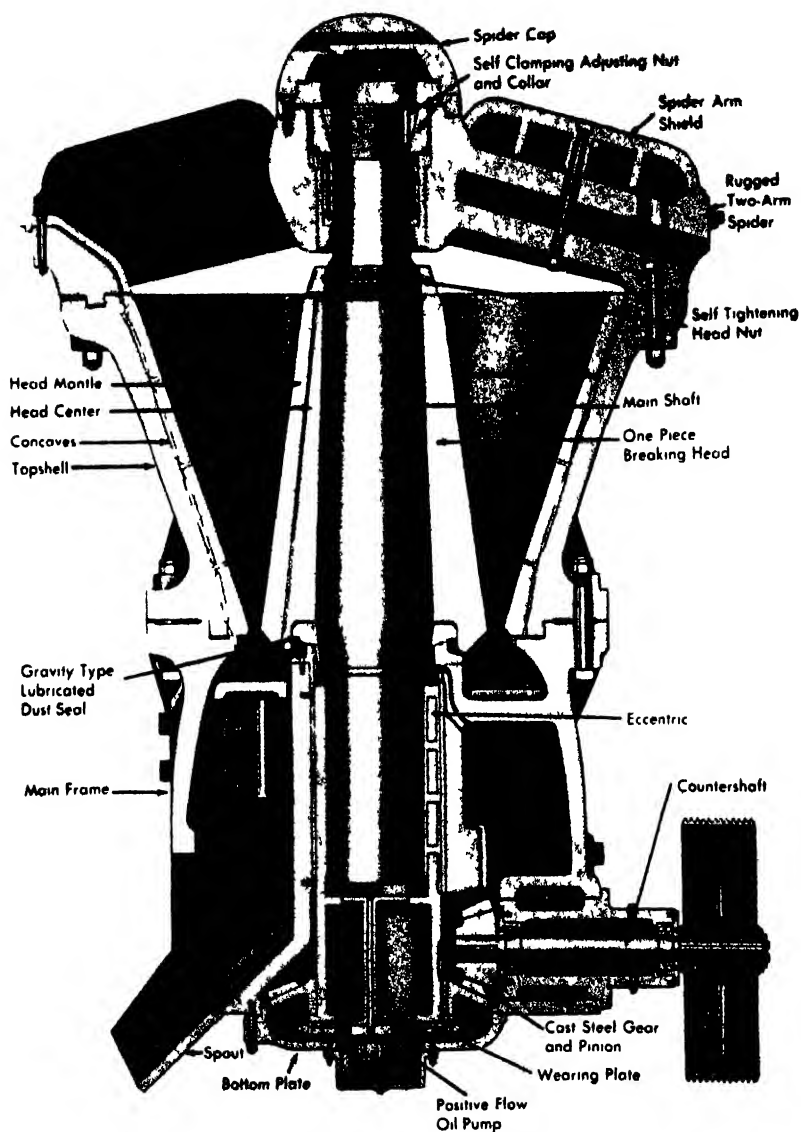


Fig. 54. Gyratory Crusher
(Courtesy Allis-Chalmers Manufacturing Co.)

crushing surfaces and is crushed when the surfaces approach while the crushed material falls through and is discharged by gravity when the crushing surfaces recede.

The angle of nip in gyratory crushers with straight-element crushing surfaces ranges from 21 to 24 degrees, with an average of about 22 degrees.

When used for crushing clays, the gyratory crusher is used as a primary crusher for breaking down large lumps of ball clays, fire clays, and shales. The usual practice is to set the crusher so that its mouth is at floor level, so that feeding can be facilitated and any bridging that may occur can readily be broken down. One man is sufficient to operate from one to three machines.

The gyratory crusher should be fed regularly and as nearly as possible up to capacity. If the feed contains particles near the largest that can be received, it is wise not to bury the crusher, as bridging may easily occur and necessitate digging aside a lot of heavy material. Some crushers are fed by chutes or over stationary grizzlies, others are fed by belt or pan conveyors, drum feeders, and shaking or vibrating grizzlies and chutes.

A comparison of Blake and gyratory crushers is given in the following table:

	Gyratory	Blake	Gyratory	Blake
Crusher opening	15-in. x 112-in.	15-in. x 30-in	60-in. x 432-in.	60-in. x 96-in.
Size of output	2-1/2-in.	4-in.	9-in.	10-in.
Tons per hour	100	58	1350	600
Horse power	53	30	275	275
Tons per h.p.	1.89	1.60	4.9	2.18
Weight - lb.	70,000	30,000	700,000	500,000

The Cone Crusher (Fig. 55) is similar in principle but different in design to the gyratory crusher. The movable crushing cone flares more rapidly toward the base thus providing an annular space between the crushing surfaces of sufficient size to accommodate the uncrushed lumps. The fixed crushing plates are curved and are adjustable vertically so as to regulate the size of the crushed particles at the discharge. The motion of the gyrating cone is effected through a combination of the actions of a gear-driven eccentric and a spindle. A lever action exerted by the spindle is partly responsible for the crushing load. The cone crusher is used principally as an intermediate crusher.

The Single-roll Crusher (Fig. 56) consists of a single roll armed with heavy projecting knobs or teeth, and a stationary breaking plate. The roll is driven by gear and pinion by means of a drive pulley. The breaking plate is hinged and held in position by bolts with a nest of compression springs under the upper nuts to permit the plate to move away when an unbreakable substance is fed. Machines are built with roll diameters 18-in. to 60-in. and lengths from 1-1/2 to 3 times the diameter and are operated at peripheral speeds of 200 to 300 r.p.m.

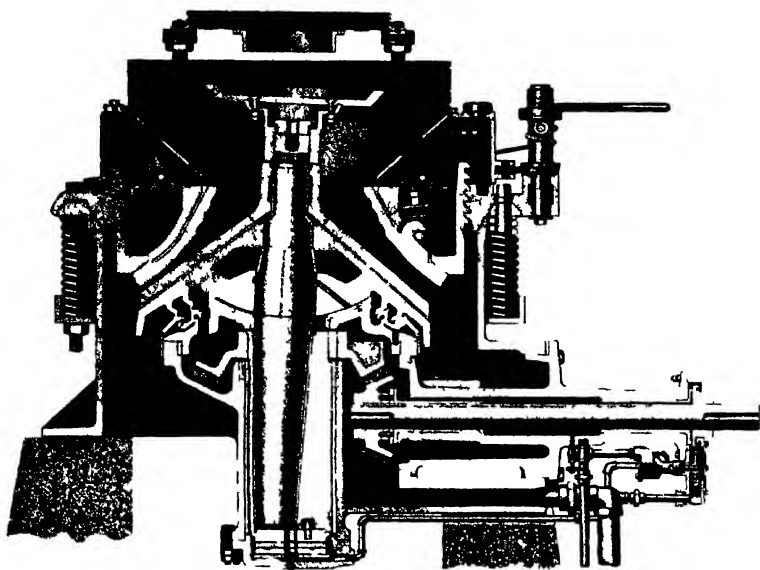


Fig. 55. Symons Cone Crusher
(Courtesy Nordberg Manufacturing Co.)

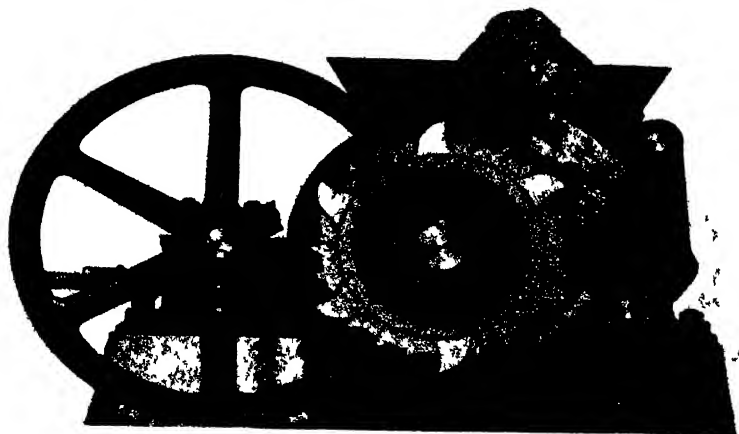


Fig. 56. Single Roll Crusher
(Courtesy The Jeffrey Manufacturing Co.)

Large lumps are broken by a spalling action as the heavy teeth strike them and break off pieces. The smaller lumps are caught between the teeth and the anvil plate and are sheared and compressed to failure between the two surfaces.

Single-roll crushers are particularly adapted to primary crushing of relatively soft or medium hard materials such as limestones, phosphate rocks, shales, slates, and hard clays.

An 18 x 30-in. roll driven at 40 r.p.m. is capable of crushing 100 t.p.h. of hard clay to a maximum size of 4 inches. The same roll driven at 50 r.p.m. can crush 60 t.p.h. of flinty clay to a 6-in. maximum size.

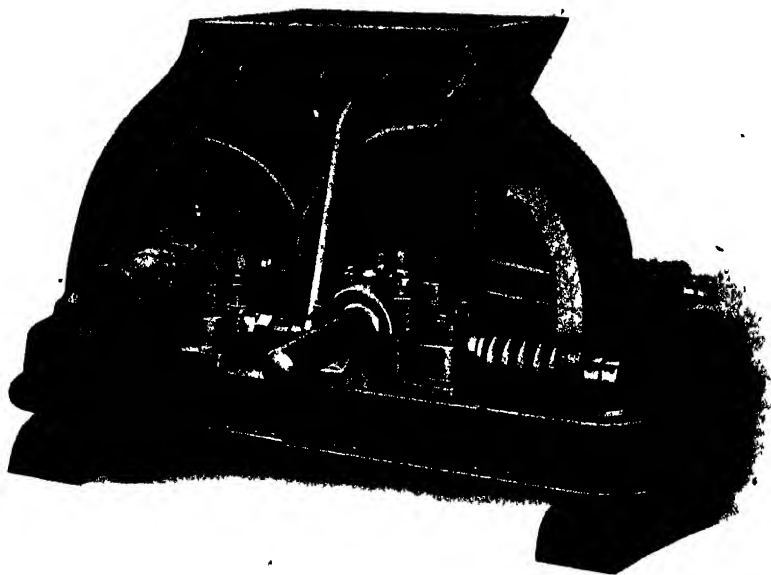


Fig. 57. Roll Crusher
(Courtesy Chambers Bros. Co.)

Rolls are of two general types: (a) rigid rolls and (b) spring rolls. Rigid rolls are seldom used because of their tendency to stall if jammed or overloaded. Spring rolls (Fig. 57) consist of two heavy cylinders, with a hardened steel surface, which are mounted on horizontal shafts and driven in opposite directions so that the surfaces are converging toward one another and downward. The gap between the rolls determines the fineness to which the material will be crushed and is adjustable by having one roll fixed and one roll movable in a horizontal plane. Each roll is usually driven independently and at slightly different speeds. The difference in speed of the rolls varies from 10 to 50 r.p.m.

and serves to turn over the oversize particles until they are in a favorable position to be nipped and crushed. The movable roll is held in position with respect to the fixed roll by means of two heavy tension rods, carrying nuts that bear at one end against the movable-roll bearings, and at the other end against a nest of springs which are seated against the main frame. The springs also act as a safety device. In case an extremely hard particle or a piece of foreign matter, such as a nut or bolt, becomes pinched between the faces of the rolls, the movable roll will move back compressing the springs and allowing the particle to pass through without damaging the roll face.

There is wide diversity in weight of a given size roll. The lighter rolls should be chosen only for small capacities or very easy crushing, or where first cost is of paramount importance. If they are used for heavy-duty crushing, lost time and maintenance costs will be excessive. Heavy rolls for heavy service will repay the additional first cost in a short time in lower repair bills and less shutdown time.

Rolls are quickly and easily adjusted as to (a) distance between roll faces and (b) lateral adjustment of one or both roll shafts. Requirements for good design in roll crushers are:

1. They should be simple in construction, compact and rugged.
2. The working parts should be readily accessible. Parts subject to wear should be so mounted and located that they can be readily replaced.
3. Springs should exert a pressure sufficient to crush the hardest material and yet should be sufficiently flexible to allow unbreakable substances to pass through without bending the shafts or breaking the castings.
4. Bearings should be designed for easy lubrication and should be well protected against dust. The problem of dust control should be considered in the overall design of the machine.
5. The mechanism for adjusting the distance between roll faces should be capable of rapid and easy operation in order to facilitate clearing the rolls in case of clogging, it should not necessitate a change in spring pressure, and it should advance both sides of the roll evenly to maintain proper alignment of shafts.
6. If possible, there should be an automatic lateral adjustment of one of the roll shafts.

The Angle of Nip (Fig. 58) is the angle formed by tangents to the roll faces at the points of contact with the particle to be crushed. For calculating the angle of nip the particle to be crushed is assumed to be spherical. In practice, the angle of nip rarely exceeds 25 degrees. The angle of nip decreases with increase in roll diameter, with increase in the distance between roll faces, and with decrease in the size of the feed particles. Therefore for coarse feed it is necessary to use large diameter rolls, otherwise the roll faces of the smaller machines must be set so far apart, in order to obtain an effective angle of nip, that only a small reduction ratio will be obtained.

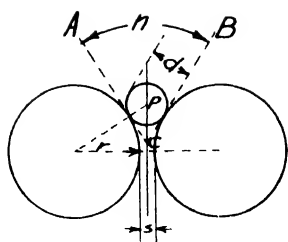


Fig. 58. Nip Angle of Rolls for a small. Periphery speeds vary between 500 and 600 feet per minute. At these speeds the output of a roll crusher will be from 10 to 16 tons per hour, with a reduction ratio of 4 to 1.

Crushing rolls are made as small as 8 inches in diameter with a 5-in. face, a speed of 150 r.p.m., and a capacity of two tons per hour, and as large as 62 inches in diameter with a 24-in. face, a speed of 50 r.p.m., and a capacity of 120 tons per hour. Data for the Sturtevant Balanced Crushing Rolls follows:

Size of Roll Diam. and Face	Feed Cubes (in.)	Roll Setting (in.)	Speed (r.p.m.)	Capacity tons/hr.
16 x 10-in.	1.25	0.61	200	26.6
	1.00	0.25	212	11.6
	0.75	0.20	225	9.8
	0.50	0.125	245	6.67
	0.25	0.065	272	3.86
24 x 15-in.	2.0	1.0	115	56.4
	1.5	0.54	130	34.4
	1.0	0.25	140	17.15
	0.75	0.20	150	14.7
	0.5	0.125	163	10.0
36 x 20-in.	3.0	1.5	59	87
	2.5	1.0	62	61
	2.0	0.5	70	34.2
	1.5	0.37	78	29.2
	1.0	0.25	85	20.9

The roll crusher is one of the best types for clays and reasonably hard shales. It is used quite extensively for crushing clays and shales used in the manufacture of structural clay products. Often two sets of roll crushers are used, one mounted above the other, so that the clay is passed first through the upper rolls for coarse crushing and then feeds directly to the lower set for fine crushing.

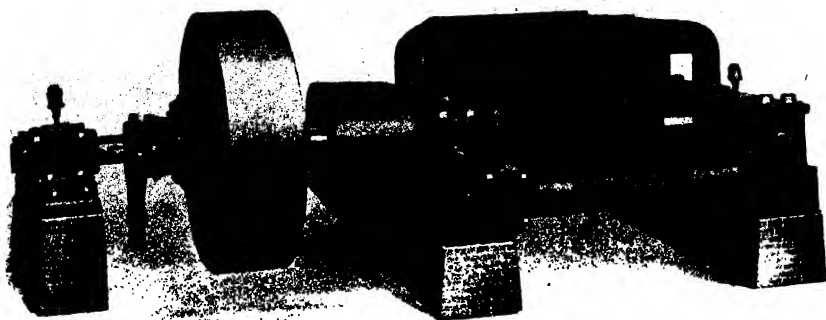


Fig. 59. Stone Extracting Conical Clay Rolls
(Courtesy Chambers Bros. Co.)

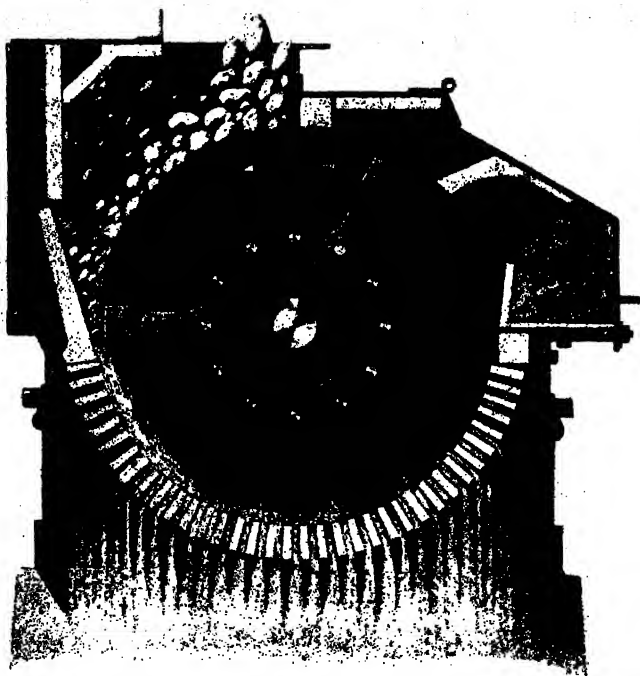


Fig. 60. Hammer Mill
(Courtesy The Jeffrey Manufacturing Co.)

Crushers with rolls in the form of a truncated cone (Fig. 59) allow coarse, hard particles of lime or other stone to be separated from the clay. The stones travel toward the end of the rolls with the larger diameter and are thrown off while the softer material passes between the roll faces. Conical rolls are used chiefly with clays that contain a considerable amount of stone, their primary purpose being to separate the stone from the clay, and as a secondary function they act as a coarse crusher. After passing through the conical rolls the clay is usually further crushed with a standard roll crusher.

There are a number of different forms of hammer mill or impactor, but the principle of operation of all mills is illustrated in Fig. 60. The hammer mill is particularly useful for clayey material that would clog reciprocating-type primary crushers. It is comprised essentially of a number of flailing hammers which strike particles either as they fall through the air, or as they rest on a stationary metal surface. When the particles are struck they are thrown with great force against fixed surfaces surrounding the hammers, or are pinched at an angle between the moving hammers and the fixed surfaces. The bottom or discharge end of the mill is made in the form of a grid or grate of various forms. The bars are usually made wedge shaped and set with broad ends inward, so as to offer a flaring discharge path and thus lessen clogging. The grate bar spacing determines the thickness of the largest particles that will be ejected from the mill, but the size of product is normally much finer than would be expected from the grate acting as a simple screen.

The dry pan (Fig. 61) is a machine designed for crushing, grinding, and screening hard clay, shale, and similar material preparatory to the manufacture of brick and other clay products. The material for use in dry pans should be practically dry so that when ground, it will readily pass through the screen plates without clogging.

In operation, power is applied to the driving shaft of the pan, which causes the main shaft and pan to revolve rapidly and, in turn, communicate motion to the crushing mullers. The mullers, which are heavy metal wheels, usually hard-faced, revolve on the muller shafts holding them in position, but do not travel around the pan. As material to be ground is thrown into the rapidly revolving pan, centrifugal motion tends to throw it to the outside of the pan, where it encounters the scrapers, which in turn throw it under the revolving mullers. This operation is repeated until the material is fine enough to sift through the screen plates in the bottom of the pan.

Below the revolving pan should be arranged a wooden platform to catch the material as it falls through the screen plates, arranged with an opening communicating with the boot of an upright bucket elevator. To the arms which hold the screen plates in position are bolted steel scrapers or wings, which catch the material as it drops through the screen plates onto the platform or stationary pan and convey it to the discharge opening.

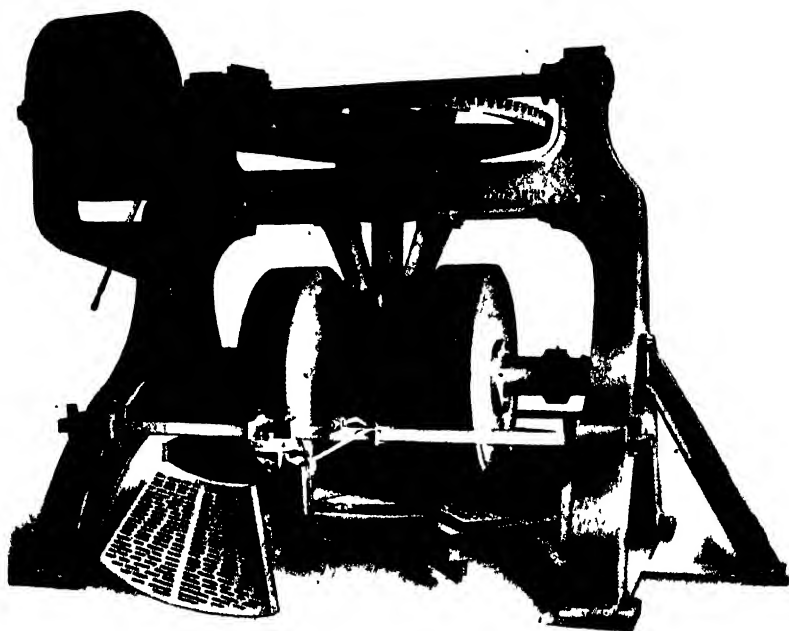


Fig. 61. Dry Pan
(Courtesy W. A. Riddell Corp.)

The usual sizes of dry pans will vary from 5 feet to 10 feet in diameter and the capacity of any pan will be governed by the nature and condition of the material being ground, and the degree of fineness required. Rated capacities vary from 1 to 15 tons per hour according to the size of the machine. The diameter of the mullers will range from 36 inches to 54 inches, and the face of the mullers varies from 7 inches to 13 inches. The weight of each muller with accessories will vary from 1750 lb. to 8300 lb. Power required will be from 10 to 15 h.p. for the smaller machines and 50 to 60 h.p. for the larger machines.

The grinder in appearance resembles the dry pan, but the operation of the machine differs in the fact that the material is not crushed through screen plates by the mullers. In all cases the material is ground between the mullers and the solid bottom of the pan. The method of discharge of the ground material differs with different makes of grinders. In one case the rim of the grinder is stationary and is set so as to leave a space between the revolving base and the underside of the rim. The material after being crushed is discharged by centrifugal force from the revolving base through the opening under the stationary rim. This opening is adjustable and regulates the fineness to which the material is ground.

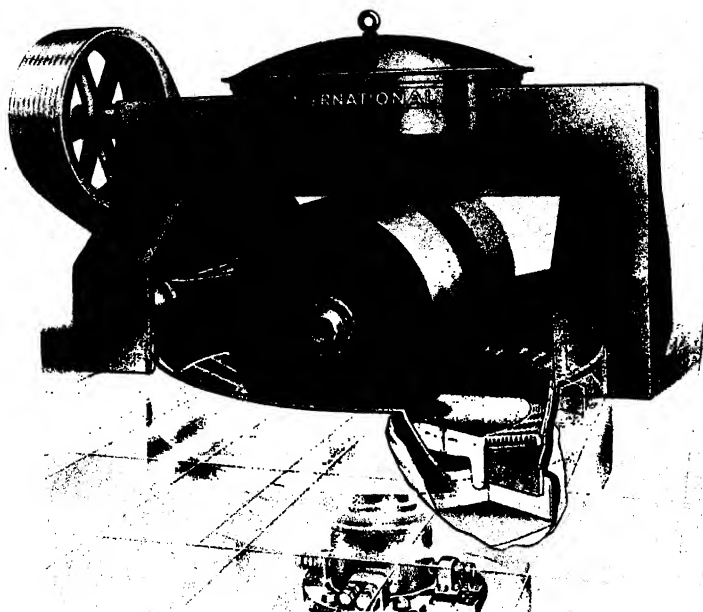


Fig. 62. Grinder
(Courtesy International Clay Machinery Co.)

Another type of grinder (Fig. 62) has inclined screen plates, around the outer edge, onto which the ground material is thrown by centrifugal force. The fines pass through these plates and are collected by means of a discharge collector while the coarse material is thrown back into the path of the mullers.

By eliminating the screen plates under the mullers, the power required to operate is greatly reduced and the capacity of the machine increased since it is possible to operate at a higher speed. Another advantage of the grinder over the dry pan is that it will handle clay too wet to go through the screens of the dry pan.

Buhr Mills consist of two flat circular stones, only one of which may rotate, or the two may rotate in opposite directions. These are made in two general types: (a) horizontal buhr mill and (b) vertical buhr mill. The horizontal buhr mill is illustrated in Fig. 63. The lower stone is mounted on a rotary table driven by a shaft and pulley. Spacing of the stones is effected by a hand wheel and lever. Feed is introduced through the hopper and drops into the central hole, works its way to the outside while being ground between the stones, and discharges

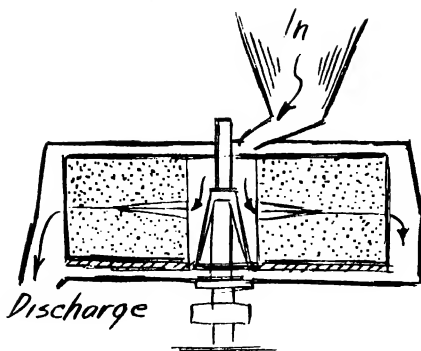


Fig. 63. Horizontal Buhr Mill

the central shaft. Ground material discharges at the bottom of the mill.

Buhr mills are used primarily for grinding soft materials such as clay, chalk, talc, salt, coal, ocher, lime, and gypsum. Feed should not exceed 1/4 inch; product ranges from 20-mesh to 200-mesh, depending upon method of operation, grooving, speed, or pressure. They have the following disadvantages:

1. Stones are difficult and costly to dress.
2. Hard substances in the feed damage the stones.
3. Efficiency is low.
4. Stones become hot when grinding is fine.

Vertical ring-roll mill (Fig. 65) consists of a heavy ring and three rollers which are pressed against the inner face of the ring by springs. The ring is revolved by a horizontal shaft. Feed from the hopper is introduced through one side of the housing by a chute. The ground product is discharged usually into a bucket elevator, thence to a screen or air classifier, which returns the oversize to the mill.

Roller mills are best suited for grinding soft or medium hard materials of non-abrasive character to medium or moderate fineness. Hard and abrasive materials cause roll faces and dies to corrugate.

✓The ball mill consists essentially of a horizontal, more or less cylindrical container holding a charge of steel, porcelain or flint balls or pebbles. The mill is charged periodically or continually with the material to be ground, and revolved; the action of the balls tumbling over one another affects the grinding.

One of the earlier forms of ball mill was the compartment ball-tube mill (Fig. 66), equipped with one or more division heads consisting of steel grates with lifters in back of these grates. Each compartment of the mill is charged with different sized grinding balls and the lifters lift the ground material from one compartment into the next, thereby effecting a stage reduction of particle size.

at the bottom. Stones are made of rock-emery or a combination of French buhr, pebble grit, and emery rock. Grooves are cut in the stones to force material outward toward the periphery; size and position of the grooves vary with the material being ground.

Vertical buhr mill (Fig. 64) comprises a fixed stone and a rotating stone carried on a pulley-driven shaft. Feed enters the machine through the hopper and is fed to the groove between the stones by means of a screw feeder on

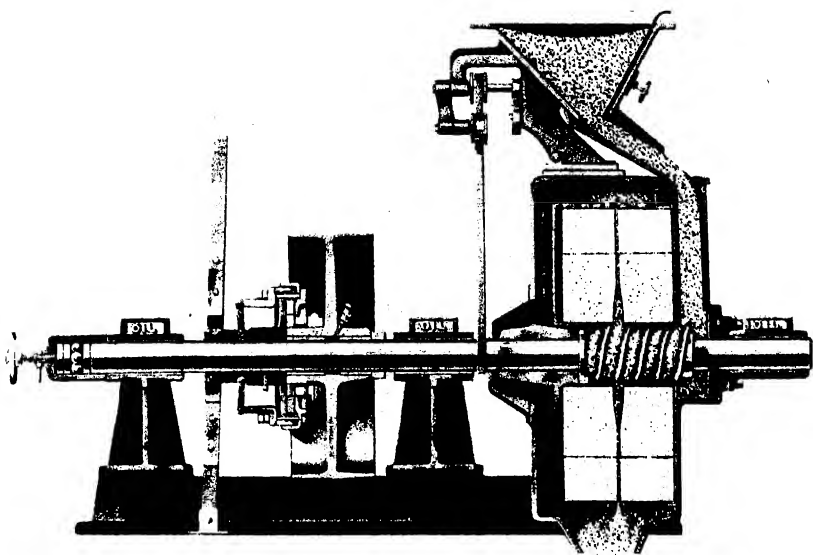


Fig. 64. Vertical Buhr Mill
(Courtesy Sturtevant Mill Co.)

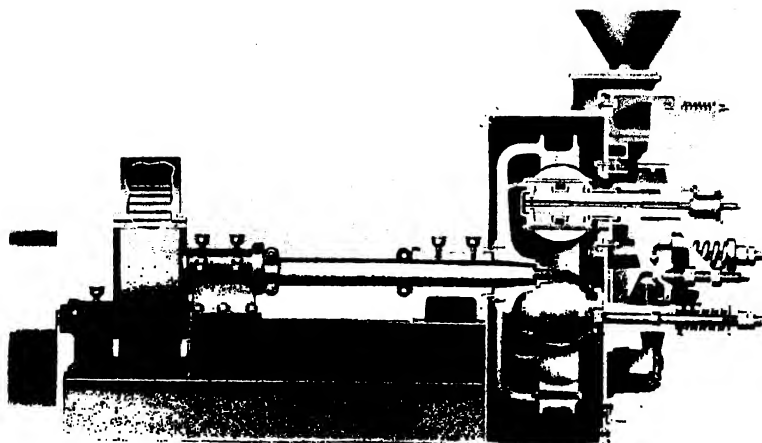


Fig. 65. Ring-Roll Mill
(Courtesy Sturtevant Mill Co.)

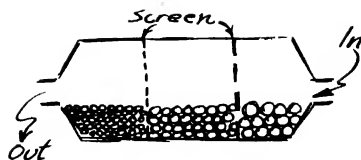


Fig. 66. Ball-Tube Mill

suitable gear and motor.

The tumbling load is the working part of the mill. It draws substantially the same amount of power whether it does any useful work or not. The amount of useful work done will differ with the shape of

The conical ball mill (Fig. 67) consists of a shell with a short cylindrical midsection, an acute conical discharge section, and an obtusely conical feed end. The cone at the discharge end makes an angle of approximately 30 degrees with the mill axis and at the feed end, 60 degrees. The whole is mounted on trunions and revolved by a

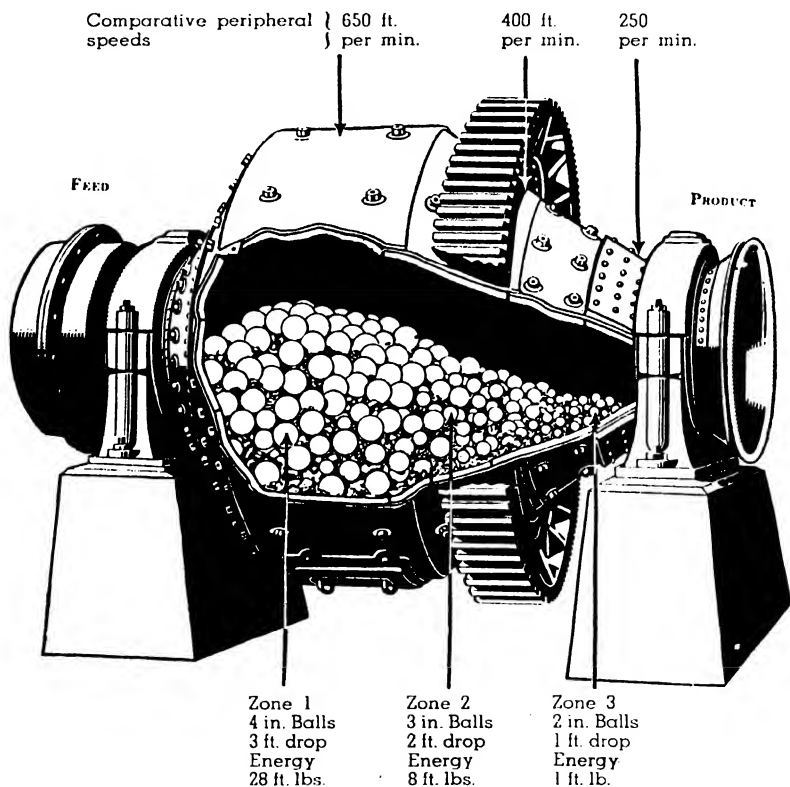


Fig. 67. Conical Ball Mill
(Courtesy Hardinge Co.)

the tumbling bodies, their size relative to the grains being ground, their quantity, and the kind of material they are made of. Loss of grinding media by wear is one of the principal items of grinding expense. Hence all of these items are of importance to efficient operation.

Spherical balls and rounded pebbles are the media used in almost all ball mills today. Prior to 1940 Danish or French flint pebbles were generally used. Since that time silica blocks and cubes quarried at Jasper, Minnesota, have been found to equal in service the Belgian sillex and imported pebbles. This stone is comprised of 94% silica, from 0.7 to 1.6% iron oxide, and potash, alumina, and lime. Pebbles from Newfoundland, North Carolina, Texas, and other localities in the United States are also being used. Zircon balls with a specific gravity of 3.7 are being manufactured and used in mills for special grinding applications. Steel balls may be used where iron contamination in the batch is not an important factor.

The shape of the grinding media determines the interstitial volume of the load. In an operating mill a seasoned charge, containing media of all sizes graded from original replacement size down to a size small enough to discharge automatically, will produce better grinding than a new charge. Usual practice is to charge a new mill with a range of sizes of balls approximating a seasoned load, and from there on make periodic changes, either adding or renewing balls of one size range, until a satisfactory grinding condition is attained. A coarse feed requires larger media than a finer feed since larger feed particles require heavier impacts.

Grinding, in the ball mill, is accomplished by two primary actions which exert a stress on the particles. The action of the balls rolling over one another tends to pinch and crush particles caught between them or against the shell of the mill. If the mill is operated at a speed sufficient to carry some of the balls to the top of the mill and allow them to drop, particles are crushed by impact as the falling balls strike the layer at the bottom of the mill. Figure 68 is an idealized representation of the action in a mill operating at a speed to cause cataracting. In the lower part of the mill the balls lie in irregular layers. The layer in contact with the shell itself is moving at substantially the same rate as the shell. Any ball in this layer between points "a-a" and "b-b" is subjected to two sets of forces as the mill rotates. One force, at the point of contact between a ball and the shell of the mill, or between a ball in one layer and one in the layer directly above it, is acting to move the ball in the direction of rotation of the mill. The second force is exerted by gravity and is applied to the opposite side of the ball and acts in the opposite direction. The second force, that of gravity, increases greatly as the ball approaches the position "b-b". This pair of forces acting on any one ball is called a couple and, since the ball is constrained by contact with the shell and with its neighbors, it rotates around an axis perpendicular to the plane of the couple. The balls in the adjacent layer are acted upon in the same way

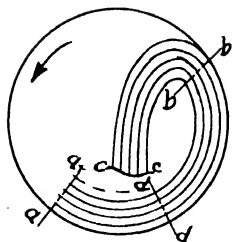


Fig. 68. Ball Paths in Cataracting

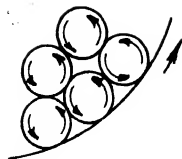


Fig. 69. Action of Tumbling Bodies in the Layers Adjacent to the Shell of a Mill

and similarly rotate. This motion of the individual balls is shown in Fig. 69. The contacting surfaces slide over one another under pressures dependent upon their depth in the mass and particles are nipped between the surfaces of the balls and ground by abrasion. Where a mill is operated at cataracting speeds, the zone "b-b" to "a-a" represents the period where the balls are falling freely and no grinding or crushing of the material takes place. At the surface "c-c" particles are continuously being struck by the falling balls and broken by impact.

Due to the shape of the conical ball mill, stage reduction is partially effected. The grinding balls tend to segregate according to size, the larger media towards the feed and the smaller media towards the discharge end. The large grain size of the feed material is broken down by impact of the larger balls at the feed end of the mill and the broken particles are further reduced by successively smaller grinding media.

Ball mills are usually lined with sectional steel or cast iron liners but in cases where contamination from iron is objectionable, mills may be lined with porcelain block or porcelain brick. Freedom from iron impurity is essential in many ceramic bodies and in such cases no iron must be allowed to come in contact with the material being ground during the process of grinding. Porcelain or flint balls are used along with porcelain lined mills. The natural flint pebbles are tough, hard, heavy, as nearly spherical as possible, resistant to chemical reaction with the material being ground, of such composition that the dust is not harmful to the ground product, and cheap.

There are few processing machines that are as versatile as a ball or pebble mill. These mills may be used (1) for dry grinding, (2) for grinding and dispersing solids in liquids simultaneously, and (3) for grinding at such high consistency that the product is discharged by injecting air into the mill to force the material down more rapidly through the interstices between the balls. A mill with this great range of adaptability also has an equally great range of operating conditions under which acceptable results may be obtained.

Operating variables are (1) mill speed, (2) the amount of grinding media, (3) the size of grinding media, (4) the size of the material to be ground, (5) the amount of material being ground at any one time, and (6) the consistency of the material being ground.

The speed of a ball mill affects the path which the balls follow in grinding. A mill may be operated at such a speed that the balls will be held to the shell by centrifugal force and have no independent motion. In this case no grinding takes place. At the other extreme the mill may be operated so slowly that the balls rise with the shell until they reach the angle of repose and then slide downward, en masse, accomplishing very little grinding. The sound of the mill will reveal either of these conditions to an experienced operator. Between these two extremes, there is a correct speed at which the balls are elevated until they are dropped freely through a distance nearly equal to the mill diameter.

The speed for correct grinding action is related to the mill diameter, and similar action is obtained in large or small diameter mills if each operates at the same percentage of its critical speed. The critical speed may be defined as the angular velocity at which the centrifugal force on a small particle, in contact with the mill shell, is equal to its weight. This critical speed, in revolutions per minute, is equal to $54.19 \div \sqrt{R}$, where R is the inside mill radius in feet.

The correct mill speed lies between 50 and 75 percent of the critical speed. If the mill is correctly charged the most rapid grinding will occur at 65% of the critical speed, and the most efficient grinding, based upon power consumption, will occur at 50% of the critical speed. When excessive slippage occurs, it can often be corrected (1) by increasing the ball charge to fill the mill to its axis, (2) by increasing the amount of the material charge, or (3) by lowering the consistency of the charge.

Considerable variation in the amount of grinding media is permissible. The charge of grinding media is a percentage of the total capacity of the mill, and the interstices between the balls are considered part of the volume occupied by the charge. The weight of the charge will vary with the size distribution of the balls. A charge of balls greater than 50% is seldom desirable. The most economical operation is usually obtained with a ball charge of between 45 and 50%, and occasionally a ball charge as low as 40% will give good results. The cascading effect will be decreased with a low charge unless the mill is operated at a higher percentage of its critical speed than for a normal charge. A low charge and high speed, however, are seldom advisable because the balls fall diagonally along the mill diameter and impinge on the mill lining instead of falling on other balls as in the case of normal operation.

The size of the grinding media is determined by the size of the largest particles to be ground, the minimum size desired in the product, the mill diameter, and the physical properties of the material being ground. When one of the heaviest balls, cascading in the mill, strikes the ore its kinetic energy must be sufficient to break the largest particle. Balls should be no larger than is required for initial crushing

because, in prolonged grinding, each size ball has an apparent limit beyond which it will no longer reduce the product. Further reduction must be obtained by the use of smaller balls. A complete screen analysis will reveal incorrect ball size. If the ground material retained on the test screen consists of large particles with chipped edges it is apparent that the grinding balls are too small to produce initial fracture.

Almost any material that has a consistency that will permit it to flow out of the mill can be successfully ground in a ball mill. High consistency means more solids per batch and greater economy. The wear on the mill lining and on the grinding media is less for material of high consistency. The grinding time, however, is increased but not necessarily in proportion to the amount of solids. The consistency of any material should be adjusted by experiment so as to arrive at the proper balance between grinding time, efficiency of grinding, and wear and tear on the mill.

In wet grinding, usually called milling, the material is added to the mill in the form of a slip. Grinding is not as effective in a wet mill as

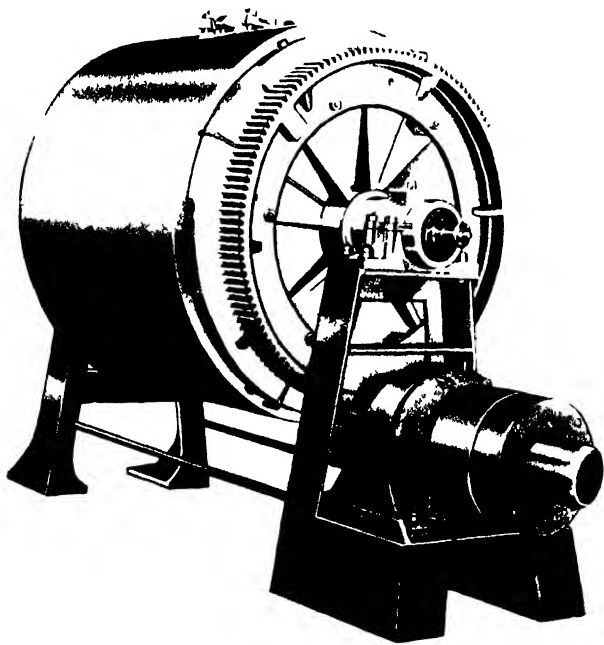


Fig. 70. Batch Mill
(Courtesy Paul O. Abbe, Inc.)

in a dry mill, since the water has a cushioning effect on the tumbling balls and breaks the force of impact. Wet mills do give fair grinding if operated for a sufficient length of time, and at the same time they provide for excellent wet mixing.

The batch mill (Fig. 70), consists of a hollow rotatable container, usually cylindrical, but also conical or other shape. The batch mill is often lined with close-fitting porcelain blocks and the grinding media are pebbles, porcelain balls, or metal balls, depending upon the application. Material to be ground is charged through the manhole and water is added if the grinding is to be wet. The closed mill is run for a time predetermined to grind to a specific fineness. Unloading is accomplished by placing a grate over the manhole and turning the mill so that the product drops through it and the pebbles are held back by the grate.

For wet grinding in a batch mill cascading of the grinding media should be avoided. The best conditions are attained when the angle of break of the balls is between 45° and 50° . The angle of break is the angle formed by a line joining the point where the outer layer of balls break from the periphery, to the centre of the mill, and the horizontal. When the speed of the mill is adjusted to give this condition the outer layer of balls and half of the underlying balls follow a downward path, rolling and sliding to provide the desired grinding action; while the bottom half is carried upward.

The ball charge should at least half fill the mill and the material charge should fill the voids and just cover the balls. This is about a 25 percent charge of material and with this charge the water content is a little less critical. An extremely heavy slurry should be avoided since it will cause the balls to pack together. A heavy consistency will also cause the balls to spread and not make contact with each other. Too thin a slurry reduces the bond between the individual balls and between the balls and lining. This permits an excessive amount of slippage. A slurry which merely permits the free movement of the balls without any floating provides the fastest grind, results in less wear to the grinding media and lining, and should produce the most uniform result.

Batch mills, as well as grinding, give a very good mixing action and are widely used for milling glaze and porcelain enamel batches. Frit, clay, coloring oxides, and opacifiers are added to the mill with enough water to form a slip and the whole batch milled for a predetermined length of time. The various ingredients tend to become uniformly ground and intimately mixed.

The rod mill (Fig. 71) has a cylindrical shell, the length of which ranges from $1\frac{1}{3}$ to 3 times the diameter. The grinding media consists of high carbon steel rods varying in diameter from 4 to $1\frac{1}{2}$ inches, with a length equal to the length of the cylindrical section of the mill. The size of rods depends on the size of feed to the mill and the fineness of product desired.

The mill is primarily a granular grinder, and its most efficient



Fig. 71. Interior View of Rod Mill
(Courtesy Hardinge Company)

application lies in the wet or dry grinding of medium-hard or soft materials from a feed size of not more than $3/4$ inch to a product not finer than 35-mesh, and where a minimum of minus 100-mesh material is needed. It will also dry-grind damp materials which cannot be handled in a ball mill. They are used in connection with the mixing of sand and lime in preparation of these materials for the manufacture of sandlime brick. They have been found more efficient for this work than dry pan. As a result of the intimate mixing and coating of the sand grains, a stronger brick is produced.

The mills are lined with manganese or chrome steel and in some cases with chilled iron liners. The consumption of rods varies from $1/3$ to 2 pounds per ton, depending upon the amount of reduction being performed and the hardness of the material. The power consumption is somewhat lower than for the ball mill, where a granular product is desired.

The Air Classifier (Fig. 72) will serve as an example of closed-circuit grinding. As the material in the mill is ground the fines pass through a grate at the discharge end and enter into a stream of air of controllable velocity. They are blown up a pipe into the outer of two

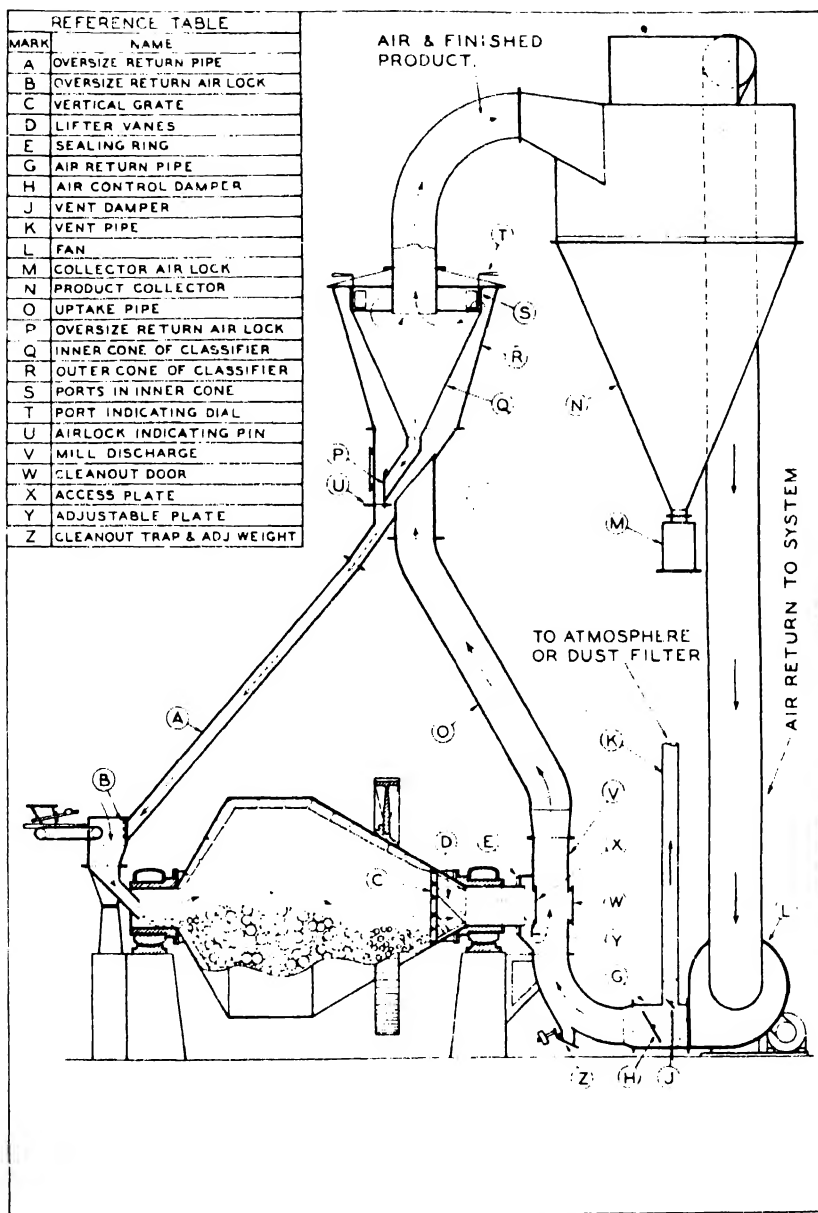


Fig. 72. Superfine Air Classifier
(Courtesy Hardinge Co.)

co-axial classifier cones. The material then enters the inner cone through adjustable ports where it acquires a centrifugal motion and the oversize particles drop out. The fines are carried by the air stream up to the product collector. The rejected oversize drops down through the inner cone and is fed by gravity to the mill for further grinding. In the product collector the velocity of the air is suddenly decreased and the fines settle out and are discharged through a spout at the bottom of the cone.

In choosing between a ball, pebble, or rod mill for any particular job the following rules can be applied:

1. Cylindrical pebble mills

- a. For wet or dry grinding in closed circuit to produce fine-ground products with nominal amount of super fines; feed size should not be more than 1/2 inch.
- b. For wet or dry coarse grinding to minus 4 to 10-mesh in open circuit or as fine as minus 35-mesh in closed circuit; feed size should not be more than one inch except on very friable material, and the moisture content should not be more than 2 percent for dry grinding.

2. Conical pebble mills

- a. For wet or dry grinding in closed circuit to produce fine-ground products with nominal amount of super fines; feed size should not be more than 3/4 inch.
- b. For dry grinding in closed circuit to produce medium-fine products with uniform grading down to finer meshes or with medium fines; high circulating loads.
- c. When equipped with superfine air classifier for dry grinding to produce uniform fine-ground products.
- d. With superfine air classifier where material being fed contains a small amount of moisture up to 4 percent.
- e. For wet or dry grinding to minus 4 to 10-mesh in open circuit; feed size should not be more than one inch except on very friable material and the moisture content should not be more than 2 percent for dry grinding.

3. Cylindrical ball, conical ball, and ball-tube mills

- a. The same general rules apply as under pebble mills, with or without classifiers, except that these mills cannot be used on materials where iron contamination is detrimental to the finished product, without porcelain liners and porcelain balls; iron contamination hardly ever exceeds 0.2 percent when using steel balls and lining; ball mills usually have 2 to 2 1/2 times the capacity of the equivalent sized pebble mills; the feed size to ball mills should not be more than 1 1/2 inches, and preferably 3/4 inches.

4. Rod mills

- a. For wet or dry grinding materials where slight iron contamination is not detrimental, and where a uniformly graded product with minimum fines below 100-mesh is needed.

- b. Should not be used for grinding finer than 48-mesh..
- c. Feed size, unless material is very friable, should not be more than 3/4 inch; larger diameter mills can handle feed up to 1 1/2 inch.
- d. For products between 16 and 48-mesh, the mill should be operated in closed circuit.

CLAY FEEDING AND PROPORTIONING

Proportioning and feeding of clays and other raw materials to forming machinery tends to (a) establish and maintain correct compositions, (b) keep machinery at optimum load, and (c) do away with expensive hand labor.

There are numerous types of mechanical feeders, but they can all be divided into two main classifications; periodic and continuous. Periodic feeders are usually reciprocating and deliver a fixed load at definite intervals. Continuous feeders, as the name implies, deliver a predetermined weight or volume of material continuously. Each of the above classes of feeders may, in turn, be divided into two sub-classes; volume-control and weight-control.

One of the simplest of the periodic type feeders is the Reciprocating-Plate Feeder (Fig. 73), which is volume controlled. It consists essentially of a hopper with a sliding plate at the bottom. The sliding plate

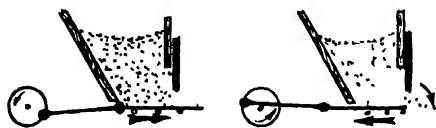


Fig. 73. Reciprocating-Plate Feeder

is actuated by an eccentric drive so that when operating it slides backward and forward with a reciprocating motion. The length of stroke is adjustable. As the plate moves forward, it pushes open a small gate at the bottom of the hopper and carries a certain volume of

material out of the hopper and beyond the gate. On the backward stroke, the gate is pushed closed and the material is scraped off the plate by the closed gate. This type of feeder is often located at the bottom of a large storage bin or hopper, so that the material may be fed automatically to a conveyor belt or directly into processing machinery. It is not a very accurate method of feeding, but it is relatively cheap to install and maintain. It finds its greatest use where extreme accuracy is not necessary but where it is desirable to prevent overloading of machinery from sudden surges of material.

Continuous bucket feeder (Fig. 74) is also a periodic, volume-control feeder. It consists of a continuous, vertical belt to which are attached a number of metal buckets. The bottom of the belt travels through a boot or container, into which the raw material is dumped. As the buckets pass through the boot, they pick up a load of material

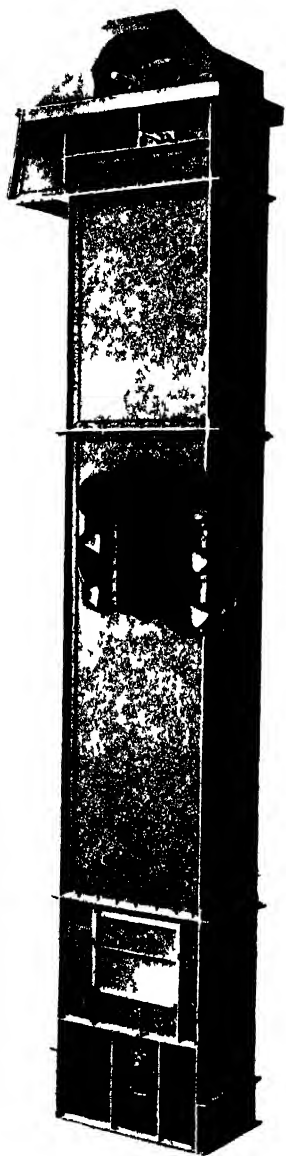


Fig. 74. Bucket Feeder
(Courtesy The Jeffrey
Manufacturing Co.)

which is carried to the top of the elevator and dumped into a chute or feed pipe as the bucket passes over the top pulley and begins its journey downward. The speed of the belt is controlled thereby controlling the amount of material fed per unit of time.

The simplest type of continuous feeders are the endless-belt type. The belt may be of rubber, canvas, or rubberized canvas, or it may be made up of a series of articulated metal pans. One type of endless-belt feeder often used in clay plants is known as the Raymond Clay Feeder (Fig. 75). It is made up of a hopper which feeds onto a short endless belt. The hopper is provided with an adjustable gate which regulates the flow of material to the endless belt. The Raymond Feeder is commonly fixed to the bottom opening of a large storage bin, and feeds material from the bin directly to the machinery or to a conveyor.

The screw feeder (Fig. 76) consists of an open top trough in which a spiral screw revolves. The metal screw has various styles of flights available for handling different classes of material. This type has the advantage of being positive in action and it can be used for damp or sticky material. On the other hand, the power consumption is high compared to other types.

The electric vibrating feeder (Fig. 77) consists of a metal trough to which is fixed an electromagnet vibrator. The high frequency and small amplitude of vibration propels the particles forward at a rapid rate of speed. The frequency is adjustable so that the rate of feed can be controlled. This type of feeder has a high degree of accuracy and is excellent for feeding relatively small amounts of materials.

The automatic disc feeder (Fig. 78) is the most widely used type of feeder

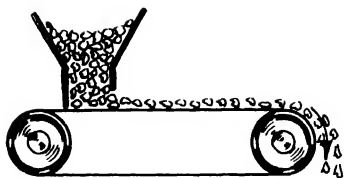


Fig. 75. Raymond Clay Feeder

in plants manufacturing structural clay products. Disc feeders consist mainly of a hopper, below which is a revolving disc. As the disc revolves, it carries the ground clay out from beneath the feeding cylinder. The clay emerges through an adjustable gate, and the size of opening may be fixed to deliver any given quantity, according to the number of revolutions of the disc.

A steel plow scrapes the clay from the disc and allows it to fall on a conveyor or into the clay working machinery. The disc feeder provides a smooth stream of clay without clogging. It is especially adaptable to the continuous operation of a pug mill.

All of the feeders so far cited have been of the volume-control type. Feeders which operate by weight-control are manufactured under a variety of names but all operate under substantially the same principles.

Hardinge constant-weight feeder (Fig. 79) is a short belt conveyor, the whole weight of which is carried by a pair of rocking beams "A", balanced on the pivot "B". The inner ends of these beams carry the



Fig. 76. Screw Conveyor
(Courtesy The Jeffrey Manufacturing Co.)

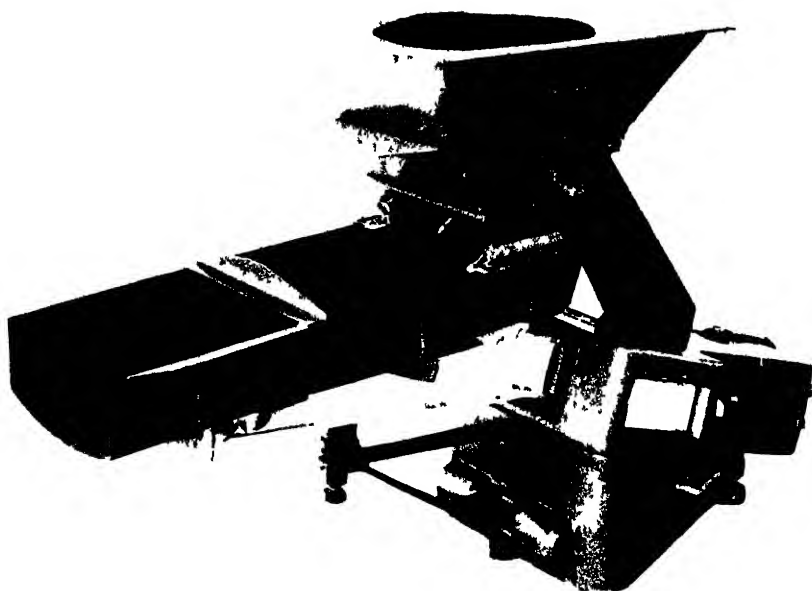


Fig. 77. Vibrating Feeder
(Courtesy The Jeffrey Manufacturing Co.)

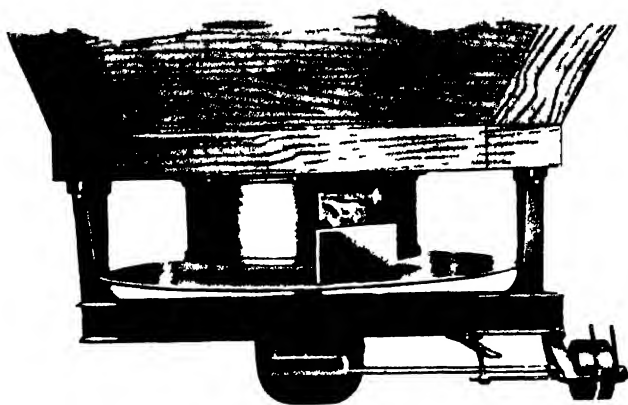


Fig. 78. Disc Feeder
(Courtesy W. A. Riddell Corp.)

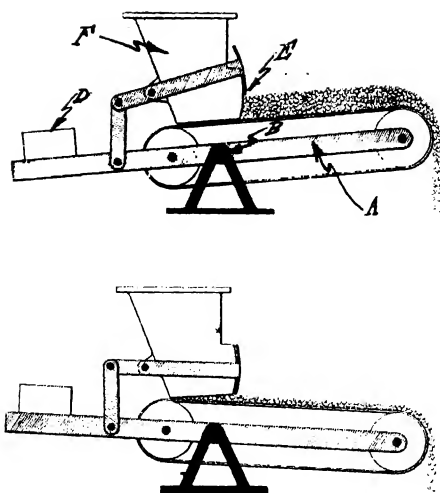


Fig. 79. Hardinge Constant-Weight Feeder
(Courtesy Hardinge Co.)

motor and the adjustable counterweight "D", and are connected through suitable linkage and levers with the gate "E" at bottom of the feed hopper "F". With the given setting of the counterweight, any excess weight of ore on the conveyor thus lowers the gate until equilibrium is restored. Also, if the weight of material on the belt is insufficient to balance the counterweight, the belt tilts upward; thus raising the gate to allow a greater volume of material to pass through until the feeder is brought to a state of balance.

This type of feeder has many uses and is particularly adaptable to feeding a ball mill. It is often connected in series with a ball mill and a control device called an electric ear. The electric ear is a radio-electric device adapted to translate differences in sound, caused by the tumbling of the grinding media in the mill, into changes in feed rate. It comprises a microphone, which is set up near the mill shell; a box containing suitable relays to actuate a switch on the feeder motor; and a panel board.

MIXING, KNEADING, AND TEMPERING

A very important step in the processing of clays is the thorough mixing of the various components that together constitute an unfired ceramic body. Kneading and tempering is the process of incorporating water into a plastic body until maximum plasticity has been attained. Mixing is the action required to blend two or more different kinds of solid materials. Mixing may be done either dry or wet; kneading and tempering always requires the use of water or other liquid.

Wet mixers. Blungers (see blungers and agitators, p. 92) are commonly used for slip preparation in whiteware plants.

Ball mills and pebble mills (see ball mills, p. 132) are used for mixing glazes and vitreous-enamel slips.

Dry mixers. The Lancaster Dry Mixer (Fig. 80) consists essentially of a vertical, gear-driven shaft which supports at the lower end, on one side a muller and on the other side a scraper. The muller and scraper revolve in a pan which contains the material to be mixed. The scraper is so fixed that it throws the material into the path of the muller, which in turn spreads the material out as it revolves. This type of mixer is made in various sizes and gives satisfactory mixing results from the small laboratory machine with a capacity of only a few pounds to the heavy duty commercial machine with a capacity rating in tons.

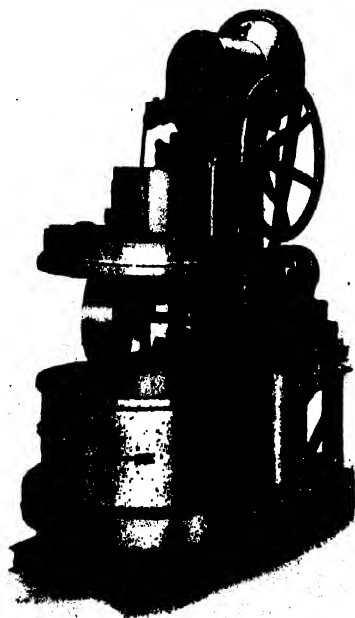


Fig. 80. Lancaster Dry Mixer (Courtesy Posey Iron Works, Inc.)

A type of mixer commonly used in preparing clays for the drypress is shown in Fig. 81. This device may be used either as a complete mixer, that is, one in which water is added to the dry clay, or as a mixing and feeding device for the clay after it has been tempered. The mixer may be placed directly over the press and the mixed clay will fall through the two holes in

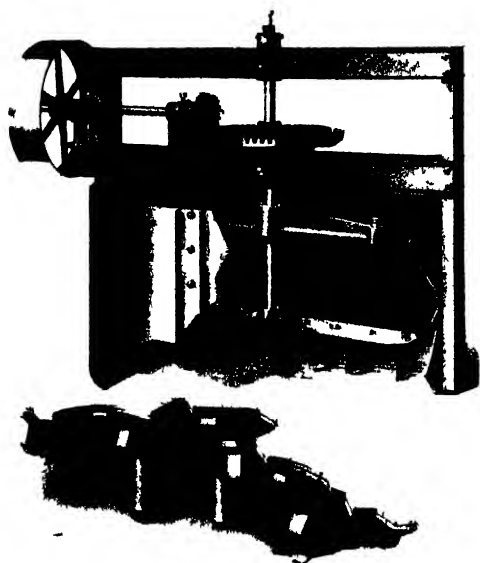
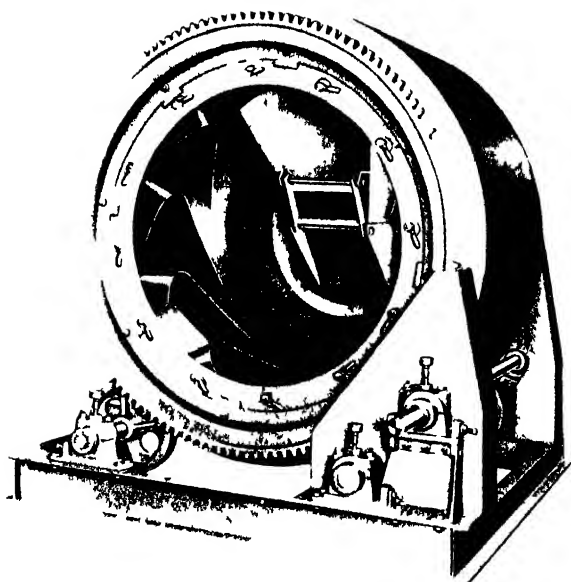


Fig 81 Clay Mixer
(Courtesy Chisholm Boyd
and White Co)

Fig 82 Sturte-
vant Dry Mixer
(Courtesy
Sturtevant Mill
Co)



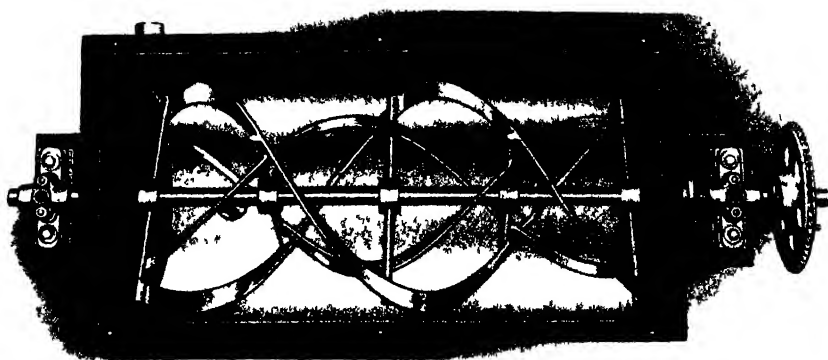


Fig. 83. Batch Mixer
(Courtesy Paul O. Abbe, Inc.)

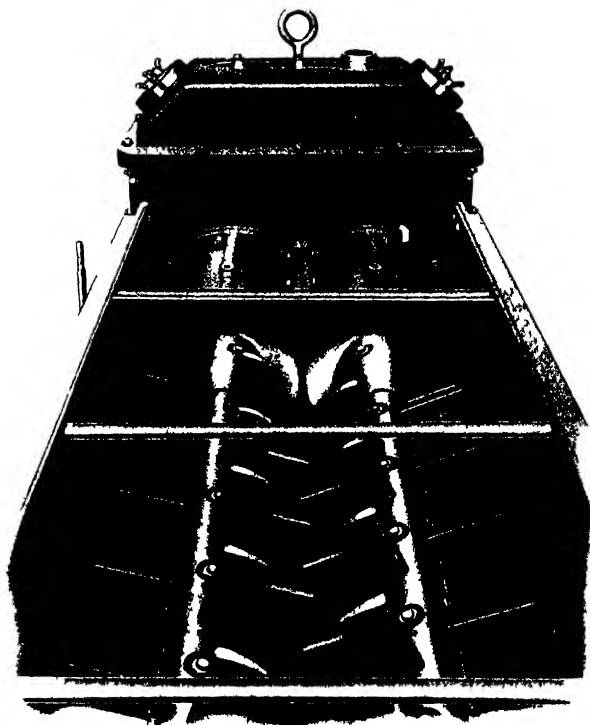


Fig. 84. Horizontal Pug Mill
(Courtesy The Fate-Root Heath Co.)

the bottom into the charging chute of the press. This type of mixer minimizes lumping of the mix and segregation of the particles.

The Sturtevant Mixer (Fig. 82) consists of a revolving drum containing a number of fins that accomplish the mixing. The weighed material to be mixed is delivered into the mixer while it is slowly rotating. The drum has only one opening through which materials can be taken in, and it is closed tightly by a valve while mixing is completed and the batch is then discharged. The one opening suffices for both ingress and egress of material.

The ribbon mixer (Fig. 83) consists of a horizontal trough containing a rotating shaft. The shaft is fixed with two metal ribbon blades spiralling both forward and backward, which revolve through the material in the mixer.

The dry mixing process in plants manufacturing dry press white-ware has certain advantages over the wet mixing process. There is (1) a considerable reduction in labor cost, (2) a better control of the moisture content of the prepared body, (3) a lower maintenance cost, and (4) a greater flexibility and a greater space economy. The dry mixing process does, however, require the use of the more expensive air-floated clays, and the handling of scrap requires more care as it must be kept free of bits of foreign matter.

Kneading and tempering is sometimes performed by hand. In preparing clays for hand molding or for hand throwing on a potters wheel, the operator makes certain that the water is thoroughly mixed with the clay by first kneading and wedging it. Wedging consists simply of cutting off as large a lump of clay as is needed to form the desired piece of ware and throwing it with some force onto a hard surface. The lump is then cut roughly in half by means of a taut wire in a holder, and the two pieces are kneaded together and again thrown on the wedging table. This process is repeated until the clay has the right "feel" to the operator.

Tempering, however, is usually done mechanically and the most widely used machines for tempering are the pug mills. Pug mills may be either horizontal or vertical.

The horizontal pug mill (Fig. 84) consists of a long semi-cylindrical trough through which pass one or two shafts carrying mixing blades. As the shafts are revolved, the blades knead the mixture of clay and water which is fed into one end of the trough. The blades have a slight pitch which serves to propel the batch slowly through the trough as it is mixed. There are usually from 4 to 6 knives per foot on each shaft. They are held in the shaft by various arrangements which allow them to be readily removed for replacement or adjusted as to pitch. The blades on a large mill are usually 8 to 10 inches long and 4 to 5 inches wide. Where pug mills contain two shafts, the shafts revolve in opposite directions and the blades are arranged to overlap several inches. A 12-foot, double-shafted mill can pug enough clay to make 15,000 building brick per hour. Pug mills are made in almost any size up to those handling enough clay for the production of 20,000 brick per hour.

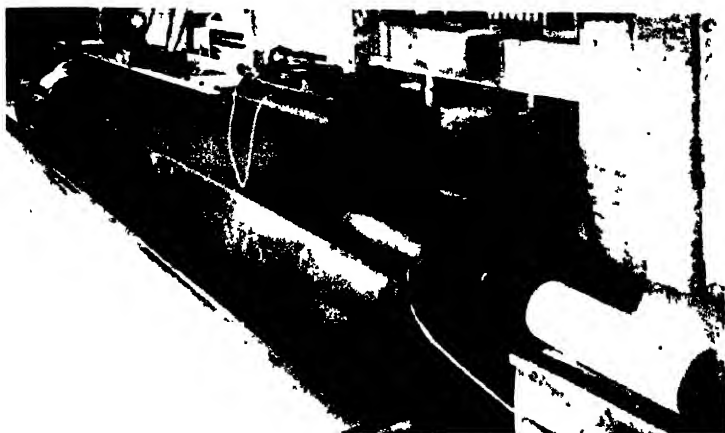


Fig. 85. Horizontal Pug Mill

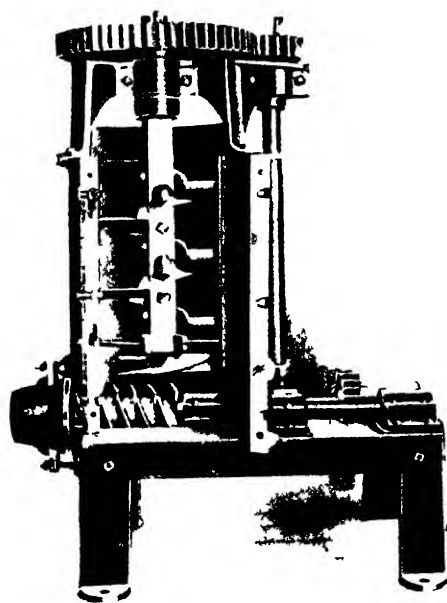


Fig. 86. Vertical Pug Mill
(Courtesy Patterson Foundry and Machine Co.)

Water for pugging may be added automatically or it may be added by the pug mill operator. A skilled operator can tell by the feel and appearance of the mud when the correct amount of water is present. Water is often added in the form of a spray; along the pug mill for about two thirds of its length. The feed of water is graduated so that the greater amount is added to the feed end of the mill.

Pug mills are used in the whiteware industries for mixing the clay and the water, and extruding blanks of plastic clay for use in the jiggering machines. Fig. 85 is a photograph of a combination pug and de-airing extrusion machine for making round blanks in a whiteware plant.

The vertical pug mill (Fig. 86) is also used in potteries for turning out blanks. It is similar to the horizontal pug mill, except that the pugging shaft is vertical. The clay is forced down by the pug knives until it contacts an auger, which forces it through a die.

The wet pan is similar in construction to the dry pan, except that it has a solid bottom in place of the slotted-grate bottom of the dry pan. Power is applied to the driving shaft of the pan, which causes the main shaft and pan to revolve rapidly and, in turn, communicate motion to the mullers. As the material is thrown into the rapidly revolving pan, centrifugal motion tends to throw it to the outside of the pan, where it encounters scrapers or plows, which in turn throw it under the revolving mullers. This operation is repeated until the material is thoroughly mixed or tempered. Unlike the dry pan, the wet pan is a batch operation. Dry clay is first fed to the pan and then water is added in sufficient quantity to produce the desired plasticity. The entire contents of the wet pan may be readily discharged either by a hand unloading shovel or with a mechanical unloader, and delivered to a suitable bucket elevator or belt conveyor. According to the size of pan, the rated capacity varies from one to eight tons per hour; diameter of mullers from 36 to 54 inches; face of mullers from 5 to 13 inches; weight of mullers from 1600 lb. to 7500 lb.; and power required from 10 to 50 h.p.

Disadvantages of the wet pan as compared with a pug mill are:

1. The initial cost of the wet pan is higher.
2. Power consumption is higher for the wet pan.
3. Wet pan is a batch operation; pug mill is a continuous operation.
4. Tempering is uneven from batch to batch with the wet pan.

The chief advantage of the wet pan is that it provides for a kneading effect on the clay and tends to squeeze out entrapped air. Entrapped air in pugged clay is a serious source of trouble, and expensive de-airing equipment is usually required to eliminate it.

DE-WATERING

It frequently becomes necessary, after having mixed a ceramic body in a fluid slip condition in a blunger, to remove a sufficient amount of water from the slip so that the body may be handled in a semi-dry, solid, or plastic condition. De-watering is the separation of the mixture of solids and water into two parts, one of which is relatively solid-free and the other relatively liquid-free, with respect to the original mixture. Substantially complete separation of water and solid is attainable only by evaporating the water.

Sedimentation is a simple method of de-watering frequently resorted to in the washing of large quantities of raw kaolins and other high-grade

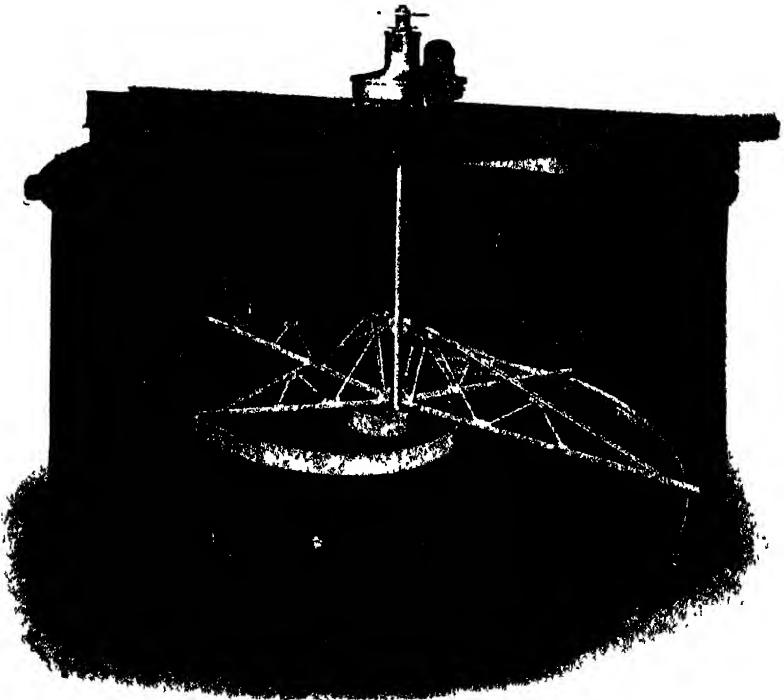


Fig. 87. Rotary Rake Thickener

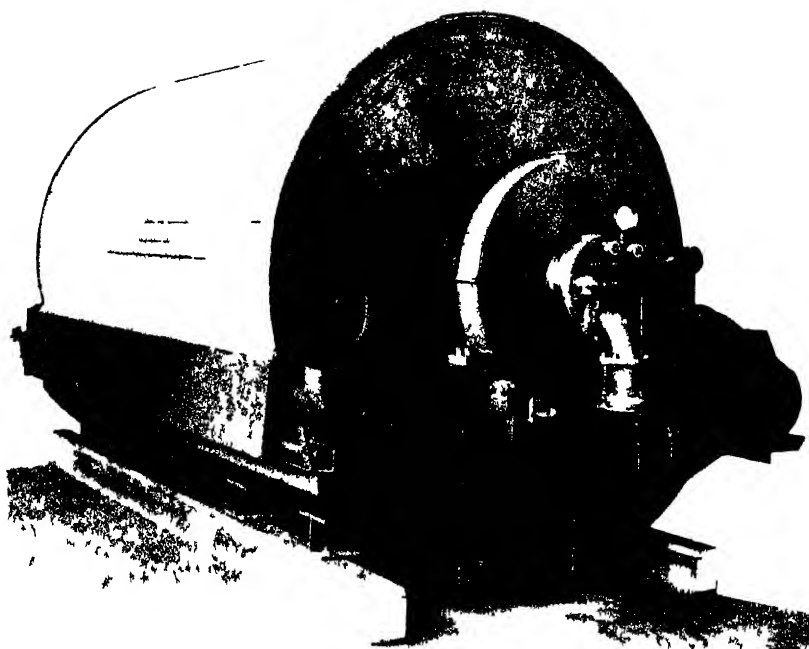


Fig 88. Drum Filter
(Courtesy Oliver United Filters, Inc)

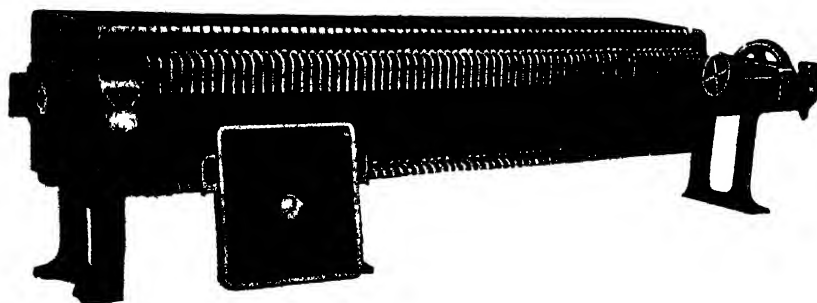


Fig. 89. Filter Press
(Courtesy International Clay Machinery, Inc)

clays. Flocculating agents are usually added to the slip to cause the colloidal particles of solid material to gather together in the form of large flocs, which settle out at a much more rapid rate than they would otherwise do.

The sand wheel, previously described, is a simple type of de-watering device usually used for relatively coarse non-plastic material.

Mechanical-discharge gravity-type thickener, (Fig. 87), comprises a cylindrical tank, shallow in comparison to its diameter, with peripheral overflow and a central bottom-discharge outlet; a centrally located feed well; and a power-driven rotary plow, positioned near the bottom, for moving settled solids to the bottom-discharge opening. In the type shown, blades on the 4-arm rotating framework rake settled solids to the central discharge core, whence thickened pulp flows through a pipe to a pump. Rake arms are set on a slope. When the feed is low-grade, solid is allowed to build up in flat-bottomed tanks to the slope of the rakes, but if the feed pulp contains much value, the bottom is frequently dished to conform with the slope of the rakes. The substantially solid-free liquid, after sedimentation, overflows the periphery of the tank and is collected in a trough and led away from the thickener by suitable pipes.

The continuous filter (Fig. 88) consists of a large drum, covered with filter cloth, which rotates in a tank of slip. A number of closely spaced parallel cords run around the outside of the drum, and a vacuum is applied inside to draw the solid particles to the cloth. At the top of the drum revolution, the vacuum is released and the thin film of solids adhering to the filter cloth is removed by means of a mechanical scraper.

Filter presses (Fig. 89) are by far the most commonly used de-watering device in ceramic industries. The commercial filter press has about 75 cast iron chambers or leaves. These leaves are either round or square, 24 to 28 inches in size, concave on both sides, and have a central hole about 4 inches in diameter. Mounted on two horizontal rails with canvas filter cloths between each pair of leaves, the assembly provides a series of 75 chambers. The slip is forced through the central holes, under a pressure of 80 to 120 p.s.i., by a mechanical pump or compressed air.

The pressure forces the water of the slip to pass through the filter cloths, while the solid particles are retained, forming a "filter cake" with a final water content of 18 to 25%.

A safety pressure valve is usually provided to shut off the pressure at some predetermined value, to prevent rupturing the filter cloths. When the press is full the limit pressure is soon reached, the pressure is shut off and the operator unlocks the assembly by a hand-wheel, separates the filter plates and removes the cakes. The entire cycle requires 1 to 1 1/2 hours, and gives a total of about 3000 lb. of body mixture.

CLAY FORMING

The process of forming ceramic articles from clays can be divided into four methods, each characterized by the amount of water used in the forming process. These may be listed in decreasing water content as follows:

- | | |
|-----------------|----------------|
| 1. Slip casting | 24 - 30% water |
| 2. Soft-mud | 18 - 24% water |
| 3. Stiff-mud | 14 - 20% water |
| 4. Dry-press | 6 - 14% water |

It will be noted that there is some overlapping of moisture content between methods. The physical properties of the raw and fired bodies are affected to a considerable extent by the forming process used. Stiff-mud products have the maximum density; soft-mud products have high porosity unless fired to vitrification; slip-cast ware also tends to have a high porosity and shrinkage due to the large amount of water removed from interstitial spaces between the grains; and dry-press ware is characterized by low shrinkage and uniform dimensions. Certain clays and body mixtures are best suited to one particular forming process, but occasionally the use of a combination of two forming processes will be found advantageous.

Clays in the dry-press condition do not contain enough water to develop a high degree of plasticity; therefore, relatively high pressures must be used to compress the clay and other particles in order to develop a bond. Dry-press machinery is designed to exert high pressures. Clay in the stiff-mud condition has developed its maximum plasticity and workability. It can be kneaded and twisted, retaining permanently any shape it has been given. Stiff-mud machinery, therefore, is designed so as to extrude a mass of plastic clay through a die which will give a desired shape to the extruded clay. When a greater percentage of water is added to a clay than is needed to develop maximum plasticity, some of the plasticity is lost, and the clay body falls into the category of soft-mud. Soft-mud bodies do not have workability to sustain a given shape if extruded through a die and, therefore, are generally formed in a mold. Fluid slip has no plasticity whatever and ware is formed by pouring the slip into a plaster mold which will absorb sufficient water from the slip to form the desired piece.

Some of the more common ceramic products formed by the above processes are given in the following table:

<u>Slip Casting</u>	<u>Soft-mud</u>	<u>Stiff-mud</u>	<u>Dry-press</u>
Pottery	Common brick	Common brick	Floor tile
Porcelain	Some face brick	Face brick	Wall tile
Sanitary ware	Refractory shapes	Paving brick	Face brick
Dinnerware	Roofing tile	Hollow block	Refractory brick
	Jiggered pottery	Drain tile	Electrical
	Dinnerware	Sewer pipe	porcelain
		Wall coping	
		Conduits	
		Refractory brick	
		Pottery	
		Electrical	
		porcelain	

Throwing by hand on a revolving wheel is one of the oldest methods of forming claywares. The clay, mixed with a sufficient amount of water, is first tempered and wedged on a hard wedging table. Hand throwing is an operation which requires the skill of an artisan. The following steps, illustrated in Fig. 90 are followed:

1. A sufficient amount of wedged clay is placed on a potter's wheel and centered by hand as the wheel is revolved.
2. Wedging is completed by pressing the lump of clay, from the sides, with the hands until it is squeezed up between the hands and then pressing it down again. This operation is repeated several times.
3. The lump of clay is then hollowed out by using the thumbs.
4. The walls are worked to final thickness.
5. and 6. The walls are formed into the desired shape.

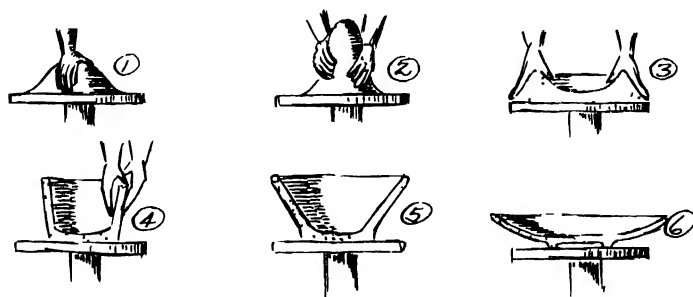


Fig. 90. Stages in Hand Throwing

There are certain limitations to hand-thrown ware, viz: (a) the piece must be circular in shape and (b) the piece can be no higher than the length of a man's arm. Higher pieces can be made in sections and the sections joined together with slip.



Fig. 91. Jigger with Pull-Down
(Courtesy Patterson Foundry and Machine Co.)

The modern jigger machine (Fig. 91) is a highly modified form of the potter's wheel. It has a revolving mechanism and head known as the "jolly" and a mounting device for the profile tool called the "jigger." The device for holding and lowering the tool is commonly called the "pull down." During the forming operation the machine is operated at a constant speed which is fixed for any particular piece. The speed may be varied by adjusting the ratio of the driving pulley to the pinion.

Two general shapes of ware are made on a jigger. One is the so-called hollow ware, which includes cups, bowls, vases, crucibles, and similarly shaped articles; and the other is flat ware, such as plates. For making hollow ware a hollow mold, shaped like the outside of the piece to be made, is placed on the head or revolving table of the jigger. Tempered clay is placed in the mold and the forming tool is brought down while the whole is revolving. The mold forms the outside, and the profile tool forms the inside of hollow ware (see Fig. 92). In case of flat ware, the reverse is true; the mold forms the inside of the piece, and the profile tool the outside (Fig. 93). The tool is made from a plate of hard steel about $\frac{1}{8}$ inch thick. A slot is cut in the upper end to allow for adjustment on the pull-down and a strip of hardwood is riveted to the back of the tool to give it rigidity and to prevent bending and chattering.

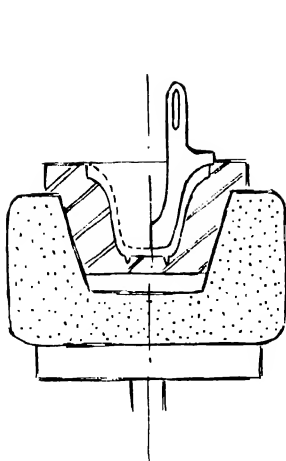


Fig. 92. Jiggering Hollow Ware

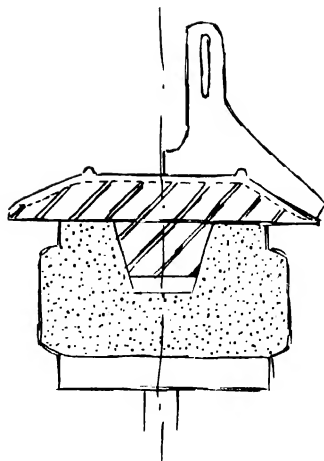


Fig. 93. Jiggering Flat Ware

In making flat ware, a clay blank or "bat" is usually formed first from a piece of the body on a separate or "batting-out" machine. The bat is a flat disc-shaped piece of clay formed by placing a lump of clay on a revolving wheel head and flattening it out with a flat disc or tool. When the bat has been formed, it is thrown onto a plate mold and is then ready for the jigger.

Oval or elliptical shapes can be made in an elliptical mold by imparting a reciprocal motion to the mold holder at the same time as it revolves. This causes the mold to describe a path such that the surface to be tooled is passed under the tool in the same manner as a circular piece would be.

Many modern plants have a wholly automatic forming process from pug mill to finished piece. Raw material is fed to the pug mill and after being tempered is extruded in the form of a round column. Slices are automatically cut from this column of clay, as it emerges from the die, by an automatic cutter controlled with a photo-electric cell. The slices are then fed to a mold which first passes under a batting-out machine, and then under a jigger. The finished piece, still in the mold, is fed from the automatic jigger onto a moving belt which carries it through a preliminary dryer, where the clay shrinks enough to allow it to be easily removed from the wheel. The empty molds are conveyed back to the jigger.

The casting process uses a mixture of clay body and water which is thin enough to be poured. The liquid slip is poured into a dry plaster mold. The mold absorbs water from the slip and builds up a layer of solid clay upon its surface. The thickness of this layer will continue

to increase until the whole mold becomes almost filled with solid clay if sufficient time is allowed and the mold is kept full of slip. When the mold is completely filled, it is called solid casting. The casting process may be interrupted at any time by pouring out the liquid slip still remaining in the mold. After a coating of sufficient thickness has been built on the surface of the mold, the mold is inverted and the excess drained out. The piece is allowed to remain in the mold until it becomes sufficiently dry and strong to be removed. It is then trimmed and finished with a wet sponge. Slip casting makes it possible to exactly duplicate ware of irregular design. The mold may be constructed in several pieces, so that intricate shapes may be easily removed.

Turning is a method of forming which is a modification of jiggering and the turning of wood on a lathe. The process is used quite widely for the finishing of some wares such as cups and bowls, which have been formed by jiggering. It is also used for the forming of electrical porcelain and steatite insulators from rough blanks of clay.

The type of lathe used is very similar to the woodworking lathe. It revolves rapidly and the finisher uses hand tools for shaping. A suitable chuck is provided for holding the particular shapes being finished. Cups are usually held from the inside by placing them over a tapered chuck.

When complete forming is to be done, turning takes place on a lathe similar to those used for metal working. Such articles as legs for lavatories, rods, and tubes, as well as insulators, may be shaped on a lathe. A hollow cylinder of clay may be supported from both ends while it is driven from one end by a friction chuck. The speed of these lathes may be slower than finishing lathes because of the deep cuts made in some of the operations.

For best results in turning, the body should be in a leather-hard condition. The clay is prepared in a stiff-mud condition and extruded by means of an auger machine. The die of the machine forms the clay into thick walled cylinders, or round blanks which may be cut to the desired length. These are then dried slowly until the clay has become rigid, but not bone dry. In this condition it is very tough and cuts readily under the tool. It contains enough moisture to form a peel rather than dust.

Hand molding is still resorted to for making complicated shapes and special bodies. Especially in the refractory industry, a large proportion of the output must be hand molded.

Ground clay is usually tempered in a wet pan and delivered to the molding tables. The molding table is merely a table or bench of convenient size and height, upon which the molder places his mold for filling and working. The molds used are almost always made of hard wood with steel strips for reinforcement. The molder first shapes a lump of clay so that it will conform roughly to the shape of the mold, but slightly smaller. This is thrown forcibly into the mold so that it will completely fill all parts of it. After the mold is filled with clay,

it is bumped several times upon the table by lifting it clear of the table and striking the bottom part of the mold against the table top. Bumping helps to drive the clay firmly against the liners and fill all sharp corners in the mold. The excess clay is struck off the top of the mold by a stiff wire, and the top slicked with a knife or trowel.

Before the clay is thrown into the mold, the inside faces of the mold are sprinkled with sand to prevent the clay from sticking. This is called "sanding the mold." When the pieces have been molded, the mold is inverted on a wooden or steel plate called a "pallet" which is used to support the pieces until they are sufficiently dry to handle.

The forming of soft-mud brick is similar to hand molding except that the various operations are partially or wholly automatic. The operation of an automatic soft-mud machine (Fig. 94) is as follows:



Fig. 94. Soft-Mud Brick Machine
(Courtesy Posey Iron Works, Inc.)

1. Clay is mixed with the proper amount of water in a chamber at the top of the machine.
2. It is then fed to a pug mill, which kneads and mixes the clay and water thoroughly.
3. The pugged clay is fed beneath a reciprocating plunger which forces

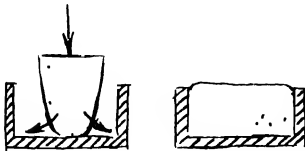


Fig. 95. Method of Filling
Molds

it into previously sanded molds, which are automatically fed from the rear of the machine. The clay is forced into the molds in such a way that the column of clay filling each compartment strikes the bottom first, and is then forced against the sides by the pressure from above (Fig. 95). This action prevents the clay from wiping the sand from the sides of the mold.

4. After the clay has been forced into the molds and the plunger rises, the mold is pushed forward under a wiper which strikes off the excess clay and slicks the tops of the bricks.
5. The molds are then carried out onto a small platform where they are struck by an automatic hammer to loosen the clay from the sides of the compartments.
6. From the hammers the mold is pushed forward to engage a dumping finger, which grasps the mold and inverts it on top of a pallet. As the mold is inverted, the brick drop out onto the pallet.
7. The loaded pallet is then pushed off the finger to engage a conveyor which carries it away from the machine.
8. The empty mold is dropped below the machine to a conveyor which carries it to an automatic sanding machine and eventually to the rear of the machine, where it is again fed to the press box.

The only manual operations required in the whole process are those of removing the loaded pallets from the conveyor and placing empty pallets on the dumping fingers.

The molds used in the automatic machine are of the same type and general construction as the ones used for hand molding. They are made of hard wood and are faced with strips of steel (Fig. 96). The molds may contain up to 10 compartments when making standard size building bricks.



Fig. 96. Six Brick Mold
(Courtesy Posey Iron Works, Inc.)

The soft-mud method of forming is especially adapted to making brick from the lower grades of clay. Its greatest use is in the manufacture of common red building brick. The clay used for this type of product is usually a surface clay. Where the clay is of satisfactory nature, it is often used just as it is mined without any preparation. The modern, completely automatic brick machine can produce 15,000 brick per hour with a crew of about six men. Colored effects may be obtained on the surface of the brick by mixing colored material with the sand used in sanding the brick.

The extrusion machine, or auger machine as it is often called, is the most important of the stiff-mud forming machines. In its simplest form, the auger machine consists of a hollow cylindrical tube containing a tight fitting screw. Fig. 97 is a diagram of a simple auger. As the screw revolves, material is carried toward the die and it is progressively compressed as it travels along. As the pressure increases, the clay is forced together into a solid column. The column adheres to the inside of the cylinder and does not revolve with the auger. Before the clay passes through the die, the final pressure is imparted to it by the end of the screw. The point of maximum pressure and forward motion of the column is opposite the tip of the screw blade. The revolving of the screw imparts an uneven pressure to the clay, which tends to give the column a circular motion. This may be counteracted by placing the die away from the screw and thus building up a reservoir of clay which absorbs the irregular motion and distributes the pressure throughout the column.

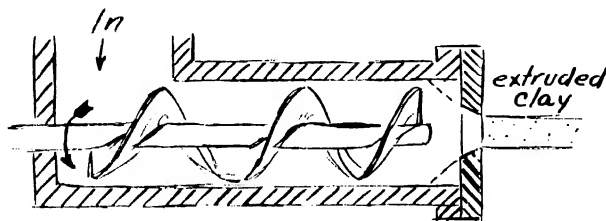


Fig. 97. Simple Auger Machine

The clay adjacent to the wall of the cylinder is retarded in its movement forward by friction and moves more slowly than the clay in the center of the column. The fact that parts of the clay column are moving at different speeds causes friction between them. When air is carried into the auger and mixed with the clay, it hinders welding of the clay and causes weaknesses in the column. The difference in speed between adjacent parts of the column gives rise to a shearing action between them. Planes of weakness are formed between adjacent parts,

and these planes of weakness divide the column into concentric layers and allow the faster layers to slip past the slower ones. The slippage may be lubricated by a layer of compressed air which retards rewelding of the clay. Once formed, these slippage surfaces remain in the column even after it has passed through the die and the finished ware has a laminated structure. Lamination is decreased or eliminated by the use of de-airing, which prevents air from being mixed with the clay in the auger machine.



Fig. 98. S-Lamination

S-shaped laminations (Fig. 98) are caused by the end of the auger shaft that protrudes beyond the end of the blade. This round shaft end leaves a round hole in the clay column as it leaves the auger (Fig. 98a) and as the column progresses toward and through the die, it is compressed and slightly twisted so that the hole progressively takes the shape illustrated in Fig. 98 b to e. Corrections for this type of lamination are (a) to change the end of the shaft to a long taper or (b) to use de-airing; or both. Cerscent shaped laminations (Fig. 99) are caused by the blades of the auger introducing air and causing planes of slippage between layers of clay. Remedies are (a) lengthen mixing chamber or (b) use de-airing; or both. Parallel laminations (Fig. 100) may be due to poor die lubrication. Proper lubrication of the die reduces friction between the die and the outside of the column of clay to a minimum and helps to prevent differential flow of clay in the column. Better die lubrication and de-airing will help to overcome this type of defect.

Feather edging or tearing along sharp edges of the ware (Fig. 101) is caused by failure of the clay to slip easily through sharp corners in the die. This is a common defect when the clay is too dry. It may be cured, in most cases, by adding more water to the clay in the pug mill or by de-airing.

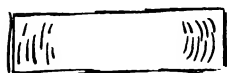


Fig. 99. Crescent Laminations

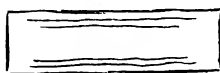


Fig. 100. Parallel Laminations

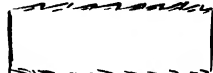


Fig. 101. Feather Edging

The dies through which the stiff mud is forced by the auger are attached to the end of the barrel of the auger machine. Fig. 102 is an illustration of a combination pug mill and auger machine. The auger is in the housing at the front of the machine, and a three-cell hollow tile die can be seen attached to the front of the auger housing. In some cases, the dies are bolted tight to the auger barrel, while in others they are hinged on one side and held in place by a shear bolt. If the pressure on the die becomes too great, the bolt will break and act as a safety valve to prevent the die from being damaged. Almost all clays require that the die be lubricated for successful extrusion. The lubricant may be either steam, oil, or water. A lubricating groove is provided back of the die for introduction of the lubricant. Fig. 103 is a lubricating brick die. It is bolted to another casting, which acts as a mixing chamber for the clay after it leaves the auger. The die is lined with a sheet steel liner which gives the final shape to the column and which may be renewed when it becomes worn. To produce hollow ware, a solid core must be introduced into the die and supported in such a way that the supports will not interfere with the shape of the column. The clay extruded around the cores forms the solid section. Fig. 104 shows how cores are supported in a die for hollow building block. Each core is held in place by means of a rigid steel bridge. The clay, before entering the die, passes around the bars of the bridge and is welded together again by the pressure. The bars are usually streamlined to minimize the friction and drag on the column. The cores must be accurately centered, as an unbalanced core causes uneven flow of the clay and produces defective ware.

To produce certain textures on the faces of extruded ware, various devices are incorporated in or attached to the dies. In the production of grooved tile, the dies are fitted with grooved liners. Rough textured brick are produced by placing a number of stiff wires at the exit of the die in such a position that they scratch the desired surfaces. Impression rolls are also used to roll certain designs or names on the column as it moves from the die.

The size of auger machines varies over a wide range. The largest may produce 30,000 standard building brick or 50 tons of hollow tile per hour, and the smallest about 1000 brick per hour. A machine extruding 15,000 brick per hour will require about 75 h.p., while one producing only 3000 per hour will need approximately 30 h.p. A combination pug mill and auger machine will require about 100 h.p. to pug and extrude the clay for 7500 brick per hour.

If the mixed and tempered clay is to be de-aired, the pug mill is usually attached directly to the auger machine with the de-airing device built in between them. Clay is fed to the pug mill (Fig. 105), where it is tempered with an addition of water. At the end of the pug-ging action, it is picked up by an auger which forces it into a short section ahead of the de-airing chamber, and here the clay acts as an air seal for the vacuum chamber. Before entering the vacuum chamber, the clay passes through a series of revolving knives which shred

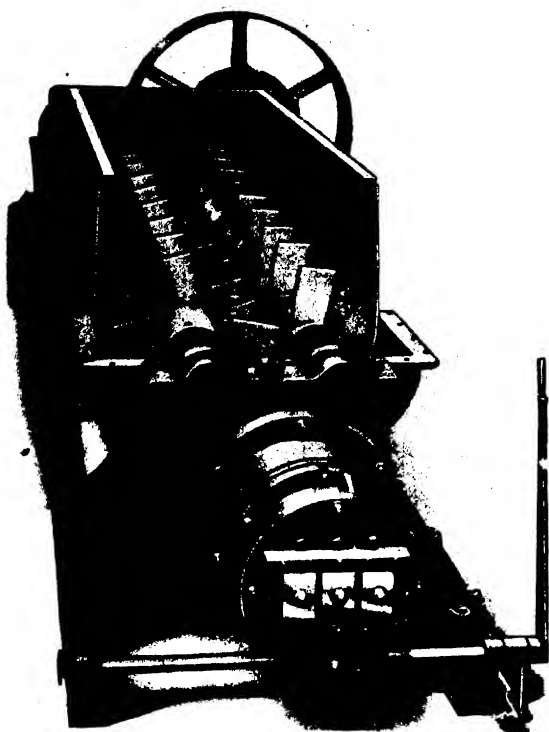
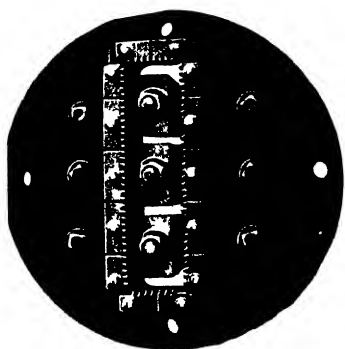


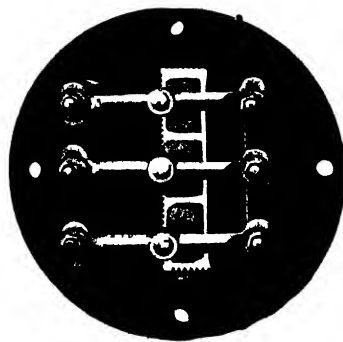
Fig. 102. Combination Pug and Auger Machine
(Courtesy W. A. Riddell Corp.)



Fig. 103. Lubricating Brick Die
(Courtesy W. A. Riddell Co.)



Front View



Rear View

Fig. 104. Die for Hollow Building Block
(Courtesy W. A. Riddell Co.)

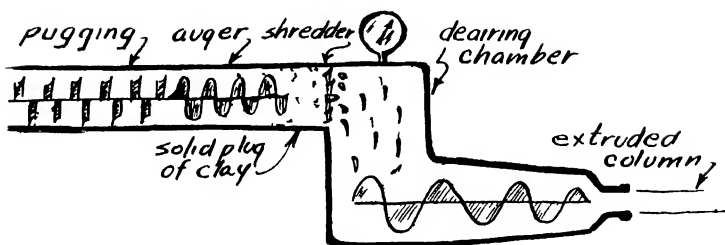


Fig. 105. Straight-Line Type De-airing Machine

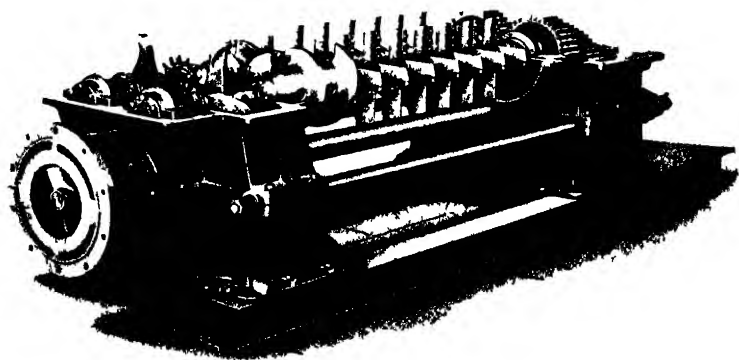


Fig. 106. Combination Pug Mill and De-airing Auger Machine
(Courtesy the Fate-Root-Heath Co.)

it in order to facilitate the removal of air by the vacuum. The shredded, de-aired clay falls to the bottom of the vacuum chamber, where it is picked up by a second auger and forced through a die in the usual manner. The clay in this auger and die chamber also acts as an air seal for the vacuum chamber. Fig. 106 is a view of a combination pug mill and de-airing auger machine with the housing removed.

The de-airing chambers of all machines are connected to a vacuum pump of sufficient capacity to maintain a vacuum of 29 inches of mercury. When a pugged clay containing adsorbed and included air is placed in a vacuum chamber, the air expands instantly due to the decrease in pressure. When the vacuum is nearly perfect (28-29 inches), the expanding air exerts a pressure of about 14 lbs. per square inch, a pressure sufficient to break through the clay. As the air escapes, it usually disintegrates the clay.

As a column of clay passes through the die of an auger machine, it passes onto a travelling belt, which carries it through a cutting machine where it is cut into sections to form the individual pieces of brick or tile. The cutting is done by a wire or series of wires stretched tight on some sort of frame. There are several types of cutters ranging from a single-wire hand cutter to multiple-wire completely automatic cutters.

Fig. 107 shows a typical brick cutter with the column of clay moving through it. This machine has a capacity of approximately 7500 standard building brick per hour. It contains three sets of cutting wires, each of which cuts 16 bricks per stroke. The wires are mounted on a circular revolving frame which, on making $1/3$ of a revolution, passes one set of the wires through the column. The entire circular frame is mounted on wheels which run on tracks. The carriage is given an intermittent reciprocating motion either by means of a reciprocating arm or by a combination of springs and arms. Before the wires are passed through the clay, the carriage must be moving in the same direction as the column and at exactly the same speed. If the speed is not synchronized between the column and the wires, the cut will not be straight. After the brick have been cut, the column moves forward until the cut portion is out of the reel. The wires then descend and cut a new series of bricks. The cut brick are pushed off onto an off-bearing belt, which has a linear speed about twice as great as the speed of the extruded column. The difference in speed causes the cut brick to be separated on the off-bearing belt by a distance approximately equal to the thickness of one brick. This separation allows the hackers to get their fingers between the bricks when picking them from the belt.

Another type of automatic cutter, shown in Fig. 108, is used chiefly for hollow tile and drain pipe, but can be used for cutting brick. The cutting wires are stretched across U-shaped bows which are mounted on spokes of a wheel. The bows are mounted by a flexible pivot, which allows them to bend back and forth from their normal position. Platens to carry the clay column are mounted on a continuous chain which moves around in unison with the column. Each platen is fitted with an

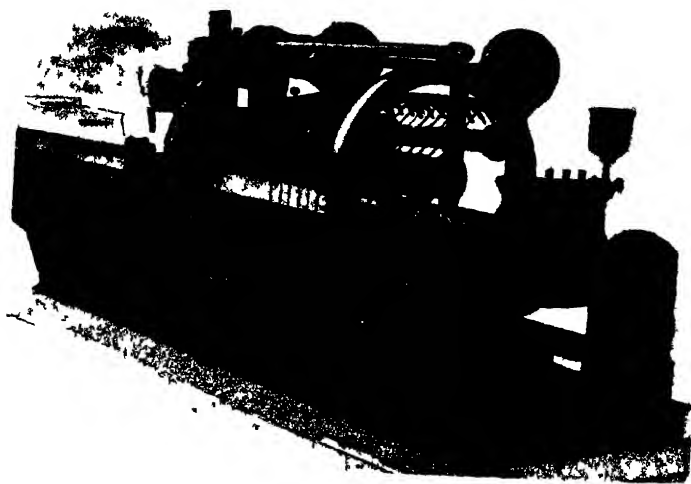


Fig. 107. Automatic Brick Cutter
(Courtesy W. A. Riddell Co.)

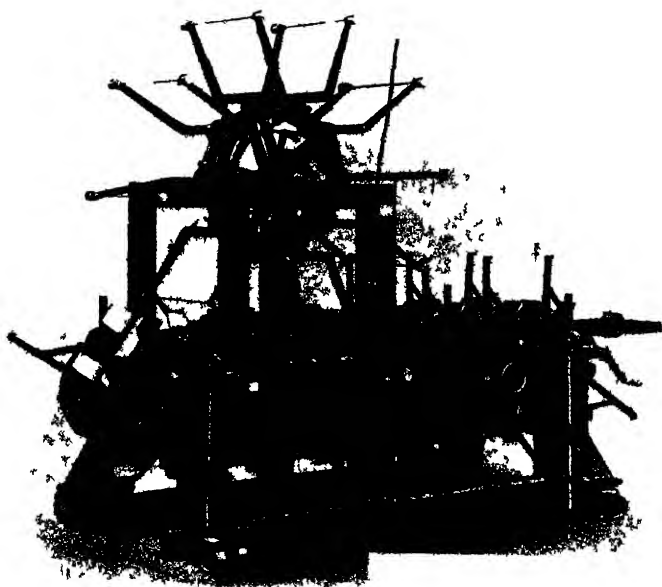


Fig. 108. Automatic Cutter for Tile
(Courtesy the Fate-Root-Heath Co.)

upright guide, directly opposite the cut. The reel is revolved by the pressure of the guides against the bows. As it revolves, the wires move downward through the clay. A straight cut is insured by the guides. When the wire has passed through the clay, it begins to rise again through the cut, still being pushed by contact with the guide. The bows are fitted with small rollers which provide a smooth and easy contact with the guides. The cut pieces are dumped from the platens as they turn under with the chain.

The sewer pipe press is an intermittent type of extrusion machine for stiff-mud bodies. Products like sewer pipe, which have sockets at one end or are curved, cannot be produced on a continuous machine such as the auger extrusion machine.

Fig. 109 is a sketch of a common type of sewer pipe press. It consists of two vertical cylinders containing pistons which are connected to one another by one or more piston rods. The upper cylinder is a steam cylinder, and the piston is given a reciprocating motion by admitting the steam alternately above and below the piston. The motion of the top piston is transmitted directly to the piston in the lower cylinder. The space below the piston in the lower cylinder is filled with clay in the stiff-mud condition. When the pistons move downward, the clay is forced through a die attached to the bottom of the clay cylinder. When the piece has been extruded, the pistons are raised and the lower cylinder is refilled with clay.

To form the socket on the end of the sewer pipe, the clay is extruded in the form of a hollow cylinder. When the cylinder of clay passes through the die, it strikes a cap (Fig. 110), which is firmly clamped to the bottom of the die. This cap is shaped like the inside of the socket, and the clay is bent around it by the pressure from above. The outside of the socket is formed by a bell die (Fig. 110), which is bolted firmly to the end of the extrusion cylinder and which has the shape of the outside of the socket. The cap which forms the inside is mounted on a table which is capable of moving away from the mouth of the die as the pipe is extruded. When the space between the cap and bell has been filled with clay, and the shape of the socket completed, the clamps are loosened and the body of the pipe rides down with the cap and table. The top of the pipe is cut by an automatic cutter at the mouth of the die, and after the pipe has been removed from the table, the cap and table are returned to their original position and clamped to the bell.

The sewer pipe press will produce pipe from 3 inches to 42 inches in diameter. The usual practice is to have two sizes of presses, one capable of producing pipe up to 18 inches diameter and the other for larger sizes. The usual steam pressure is about 120 lb. per sq. in., while the pressure developed in the clay cylinder is about 800 lb. per sq. in. This is attained by having a larger piston in the steam cylinder than in the clay cylinder.

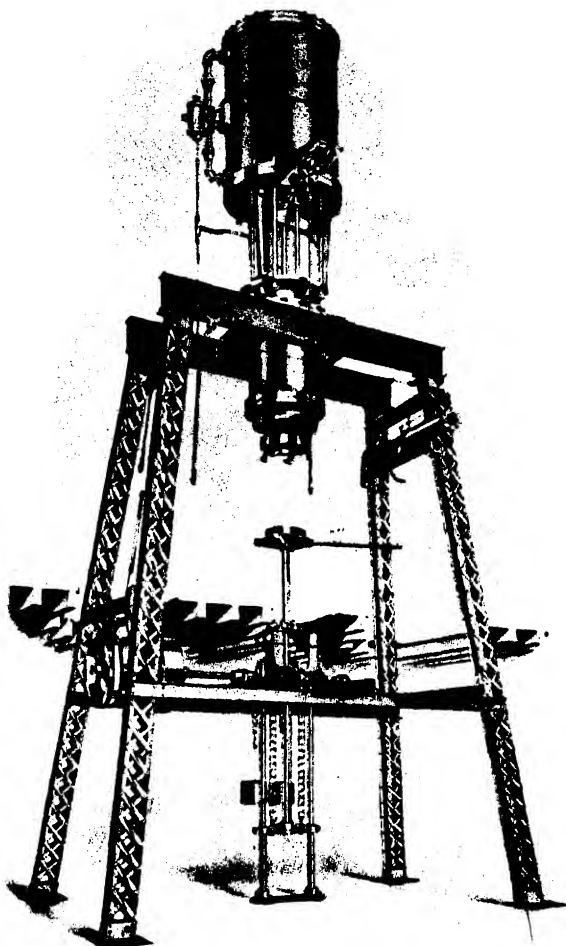


Fig. 109. Sewer Pipe Press
(Courtesy W. A. Riddell Co.)

The raw clay is prepared for the sewer pipe press either by tempering and mixing in a pug mill or a wet pan. The mixed clay is then carried to the machine and charged through a hole near the top of the clay cylinder. It is fed in, usually by a belt conveyor, while the piston is at the top of its stroke. As the piston descends, the lumps of wet clay are compacted. This operation is usually done as slowly as possible to allow the entrapped air to escape from between the lumps as they are pressed together. The cylinder may be equipped with valves

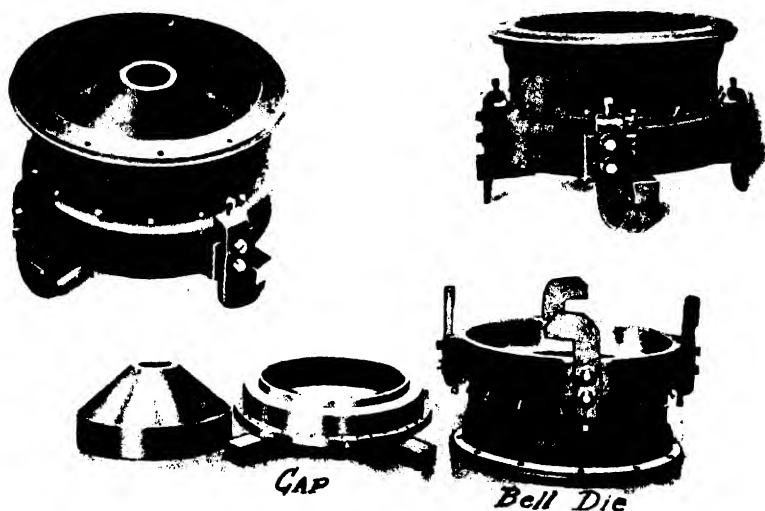


Fig. 110. Sewer Pipe Dies
(Courtesy W. A. Riddell Co.)

to release the air which escapes from the clay. Some operators use a pug mill and then de-air the tempered clay and extrude it through a die with a short auger. This clay is then broken into lumps and charged into the sewer pipe press. In other cases, the clay cylinder of the sewer pipe press is under vacuum and the clay is de-aired after it has been fed into the machine.

Sewer pipe elbows and curves may be made on a press if the clay is plastic enough to withstand bending. For producing curved pieces, the die is fitted with an adjustable slide which allows the distribution of the clay around the core to be varied. This device allows more clay to flow from one side of the mold than from the other, thus producing a cylinder that is longer on one side than on the other. Goose-necks and traps may also be produced by changing the slide so that it first produces a bend in one direction and then in the opposite direction. Odd shapes such as T's must be made by cementing two or more pipes together while they are in the plastic condition.

Dry Press Process. A typical toggle press of the type used for refractories and face brick is shown in Fig. 111. This press makes four brick with each stroke of the plunger, has a capacity of approximately 2000 nine-inch brick per hour, and it requires from 15 to 20 horsepower to operate. Four, five or six mold presses are available.

The power is transmitted to the machine through a large pulley which drives a small pinion directly geared to a large wheel. The large wheel carries an eccentric which imparts a reciprocal motion to an arm which causes plungers to move in and out of the molds.

The operating cycle of the press is illustrated in Fig. 112, and is as follows:

1. The tray containing the clay moves over the molds and discharges material into them.
2. The tray moves back, and at the same time scrapes off excess clay.
3. The top ram descends and compresses the clay while the bottom ram stays stationary.
4. The top ram stays stationary while the bottom ram compresses the clay from below.
5. The top ram ascends as the bottom ram also rises, and pushes the brick onto the table.
6. As the tray moves forward to refill the molds, it pushes the already formed brick out of the way.
7. The entire operation is repeated.

As the top ram descends in operation "3," air is entrapped and compressed. By allowing the top ram to remain stationary at the bottom of its stroke and applying pressure through the bottom ram (operation "4"), the greater part of this entrapped air is forced out. Pressure from the bottom also helps to make the brick more uniform from top to bottom. Rams are sometimes perforated to aid the air to escape.

The press design is such that, regardless of the amount of clay charged, successive brick from the same mold chamber will be pressed to exactly the same dimensions, including thickness. This is true because the minimum distance between the upper and lower die is controlled. Therefore, the pressure in the toggle press is controlled by the amount of clay charged and the best measure of pressure is obtained by weighing the green brick. The distance between the upper and lower dies is adjustable by means of a wheel, located at the front of the press, which raises or lowers the bottom dies.

De-airing can be applied to dry pressing by the almost instant evacuation of the mold cavity between the time the press pads have entered the mold and the maximum pressure is reached. The press pads are equipped with numerous tiny holes, a few thousandths of an inch in diameter. These holes, which are too small for the particles to enter, are connected by means of hollow tubes and flexible hose to a large vacuum tank. De-airing has the advantage that pressure cracking is practically eliminated and much higher pressures can be used, resulting in denser, stronger brick, and a substantial decrease in porosity of the fired brick.

Presses may be either mechanically or hydraulically operated. Although the hydraulic press gives a more even and uniform pressure, it is not as widely used as the mechanical press, as it is much slower in operation.

Advantages of the dry-press over the stiff-mud method of forming ware are:

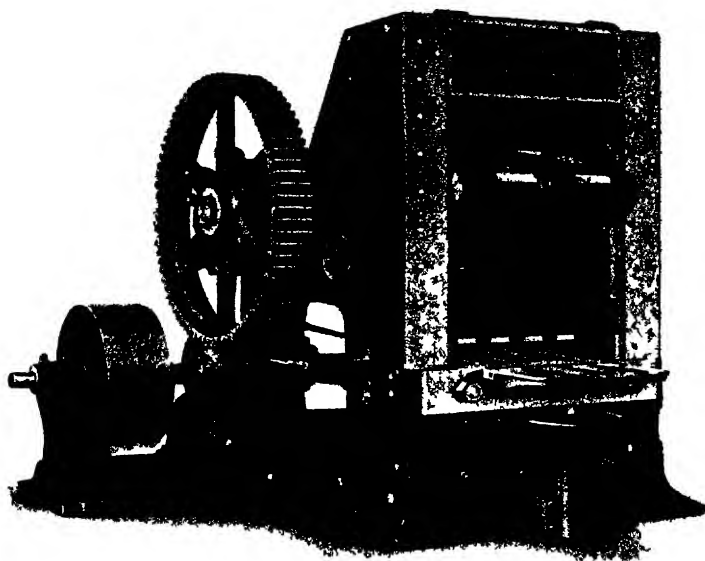


Fig. 111. Toggle Brick Press
(Courtesy Chusholm Boyd and White Co.)

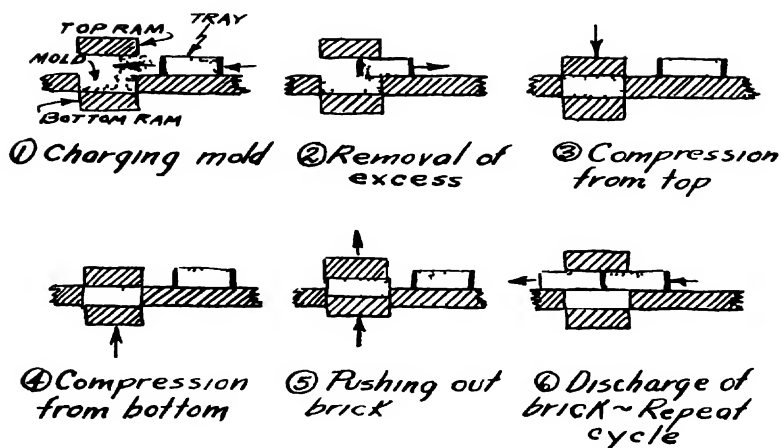


Fig. 112. Operating Cycle, Dry Press

1. Fired ware retains the exact shape of the mold.
2. Dry-press ware has low drying shrinkage.
3. Due to the small percentage of water used in tempering dry-press clays, little or no drying is required before firing.
4. Laminations are more easily controlled than with an extruded clay.

Disadvantages are:

1. Dry-press ware is more porous than stiff-mud ware.
2. Dry-press brick have lower resistance to freezing and thawing than stiff-mud brick.
3. Dry-press ware has lower resistance to abrasion.
4. Dry-press ware in the unfired or green state is more easily chipped and requires greater care in handling.
5. The thickness of dry-press ware is limited to the ability to obtain a uniform pressure throughout the piece.

To facilitate the removal of the piece from the mold, the dies are often heated by electricity or steam.

The stiff-mud extrusion machine is not capable of producing brick with true dimensions, smooth faces and sharp corners. Since these features are required in many types of firebrick and refractory shapes, whenever these products are formed with an auger machine an additional operation, called repressing, must be resorted to.

The primary function of the repress (Fig. 113) is to modify the shape and dimensions of the brick and also in the same operation to brand it.

The brick are fed to the machine two at a time, directly from the cutter of the extrusion machine. They are generally stiff enough to be pressed without preliminary drying and may be cut nearly to final dimensions, which lessens the work to be done by the press. When the brick are fed onto the press they are engaged by a frame, which pulls them over the molds into which they drop. The charging mechanism then retreats as the plungers descend into the molds. As the top plunger comes down, the bottom of the mold also descends but at a slower rate than the top plunger. The bottom plunger may begin its upward stroke slightly ahead of the upper plunger, thus exerting a heavy pressure on the clay. Since the top plunger moves at a greater rate than the bottom one, it releases the pressure rapidly on the up-stroke. The bottom plunger reaches a position which is just flush with the table of the machine, so the pressed brick may be pushed away by the charging frame as it advances with two unpressed brick.

The screw press is used for making relatively small dry-press pieces in the whiteware industries. Such products as electrical insulator parts, stove plates, knobs and caps for exposed wiring and many other parts are made in a screw press. Fig. 114 illustrates the principle of the screw press. The type shown is a hand operated press. It consists essentially of a vertical screw which moves up and down and is held steady at the lower end by means of a brace which slides

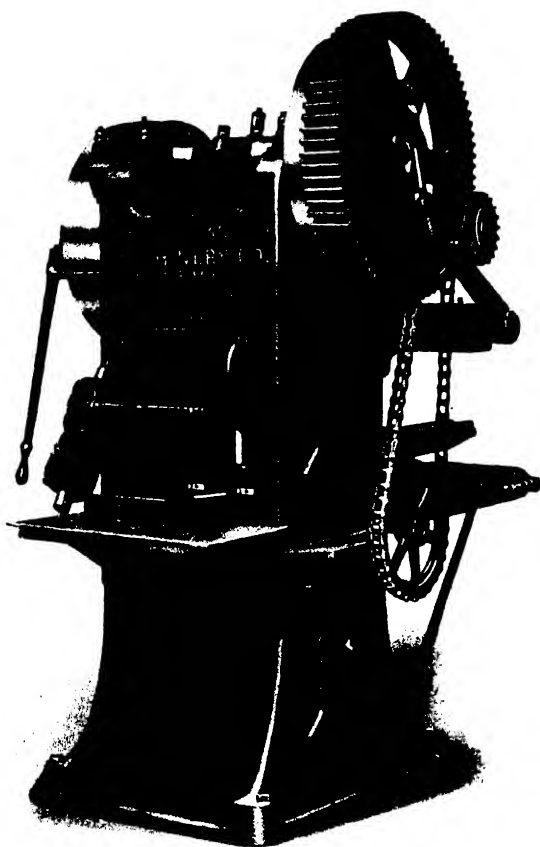


Fig. 113. Repress
(Courtesy W. A. Riddell Corp.)

on two supporting posts of the frame work. To the lower end of the screw is affixed the upper die, and the lower die is fastened to the base plate of the press. The screw is operated by means of two long handles and the lower die is fixed to a vertical rod, underneath the press, so that it is free to move up and down actuated by a foot pedal.

The operator fills the die box with clay and brings the upper die down into the die box to compress the clay. The upper die is bumped several times to thoroughly compact the clay and drive out as much air as possible. At the same time, pressure is applied to the foot pedal to exert some pressure from the bottom die and distribute the pressure more evenly throughout the piece. The upper die is then

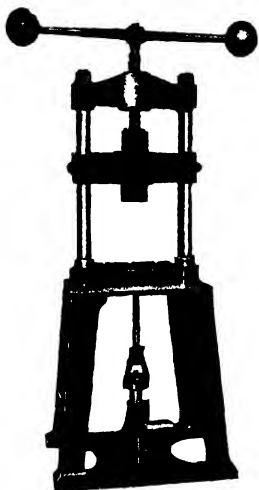


Fig. 114. Screw Press
(Courtesy Crossley Mach. Co.)

raised and by stepping on the foot pedal, the lower die is brought up until it pushes the finished piece out of the die box.

Larger and heavier screw presses are mechanically operated. They are of the same general principles as the hand-operated press.

Tabletting machines (Fig. 115) are designed to turn out very small pieces such as small porcelain or steatite insulators, of a wide variety of design. They are of the toggle press type and have a single upper plunger. The dies, which are multiple in number, are fixed in a rotating table in the form of a circle. As the table rotates, the dies first pass under a hopper which fills them, and then under the plunger where the piece is pressed. At the end of the cycle, the finished piece is ejected and slides down a chute into a container. Typical ceramic products produced with this type of press are illustrated in Fig. 116.



Fig. 115. Tabletting Press
(Courtesy F. J. Stokes Machine Co.)

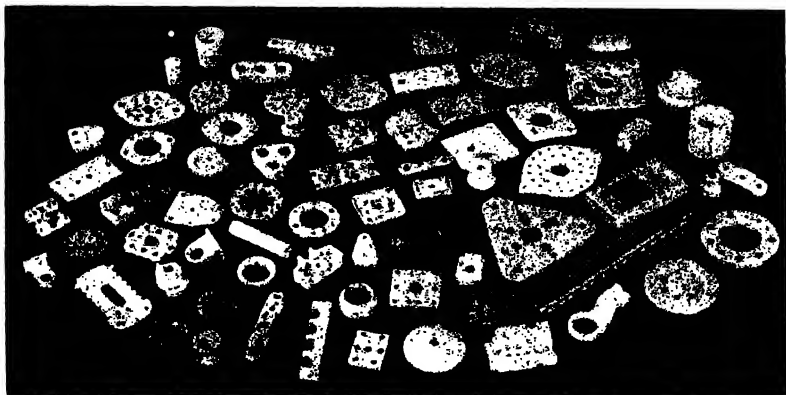


Fig. 116. Typical Compressed Powder Parts
(Courtesy F. J. Stokes Machine Co.)

Chapter 20

FLOTATION

Since most of the methods used for beneficiating and treating ceramic materials have been adapted from the mining and mineral dressing fields, it is not surprising that the ceramist has of late been investigating the many possibilities of froth-flotation for purifying clays and other ceramic raw materials.

Froth-flotation is a method of concentrating solid minerals in a relatively finely-divided state. It is essentially a method of gravity concentration in water, in which the effective specific gravity of certain minerals is substantially decreased by causing air bubbles to attach more or less tenaciously to particles of that particular mineral, whereupon they float on the separating medium while the unaffected minerals sink.

In essential outline, the ordinary simple froth-flotation operation comprises the following steps:

1. Grinding the ore in water to a maximum size of 35 to 48-mesh.
2. Dilution to a pulp consistency of 15 to 35 per cent solids.
3. Addition to the pulp of small quantities of one or more various inorganic conditioning agents, which have a number of functions.
4. Addition of collector reagent which has the function of coating the mineral to be floated with a water-repellent film.
5. Addition of a frothing agent, which imparts persistence to bubbles when they reach the surface.
6. Aeration either by agitation, or by air injection, during which the coated mineral particles become more or less firmly attached to gas bubbles.
7. Separation of mineral bearing froth from a liquid pulp containing residual particles which did not take on collector coatings.

A flotation machine and its contents, in continuous operation, comprise a system in a rough sort of dynamic and chemical equilibrium. Into this system ore, water, air and a variety of chemicals in small quantities are introduced continuously; from it flow continuously two or more streams of products which differ obviously in physical state and somewhat less apparently in chemical composition. The overflow stream is usually a froth carrying a load of solid which is different in mineralogical character from that of the other product streams and of the feed stream.

The chemical reagents which are added to the pulp have a variety of functions. In order to separate two different minerals, "A" and "B,"

it is necessary to choose a reagent that will wet "A" and not "B," or one that will wet "B" and not "A." The mineral grains that have thus been made water-repellent will cling to air bubbles and be carried to the surface, while those which are water-wet will sink to the bottom. Such reagents which render selected minerals water-repellent are called collectors or collecting agents.

The essential prerequisite to separation by flotation is selective collector-coating. Since the composition of any pulp is a suspension of two or more different minerals in water which may or may not have dissolved, to a greater or lesser extent, soluble impurities from the minerals, it can readily be seen that no two suspensions of mineral pulp are likely to be exactly the same in chemical composition. The power of reacting of the collecting reagent is often affected and sometimes neutralized by chemical reaction with the soluble salts and other impurities in the pulp. To counteract this, a reagent must be added that will protect the collector from undesirable chemical reaction which would prevent it from performing its function. Such reagents are called conditioners. They may be divided into two classes; activators and depressors. If it is desirable to prevent collection of a certain mineral, a depressor is added. Such changes in surface of the mineral as aid collection of the changed particle are called activation; surface changes that prevent collection are called depression; changes in the solution which do not at the same time effect changes in particle surfaces are usually designed to protect other reagents and are, therefore, called protection. Activators, depressors and protectors are all classed as conditioning reagents, since they condition the pulp to receive the collector.

The term frothing, in flotation, means the maintenance of a body of bubbles at and above the upper surface of the flotation pulp. The liquid walls of these bubbles contain ore particles either at rest or in motion, or in both states. The functions of the froth are:

1. To change the effective density of the minerals included in it to an extent that permits them to rise instead of fall in a quiescent pulp.
2. To permit differential drawing back of gangue minerals into the body of the pulp.
3. To maintain a body of ore particles above the pulp long enough to permit such drainage to effect more or less concentration.
4. To transport floated material horizontally to the concentrate discharge point.

A froth is simply a collection of bubbles. Prolongation of bubble life is, therefore, an essential element in frothing. Sufficiently long life is necessary to give time for the desired draining and horizontal transport. Beyond such time, however, further life is a nuisance, since froth is difficult to transport and de-water. The draining function is best served by a relatively large bubble froth, comparatively thick walled, with plenty but not an excessive amount of internal movement. Pure water does not froth, and the more or less contaminated waters

of pulps froth very little. The addition of minute quantities of certain reagents, such as cresol or pine oil, produces frothing and increases the effective resistance of the bubble walls to external strain.

A flotation machine is an apparatus to carry out a flotation process. They usually consist of a series of substantially identical cells set side by side on the same level, with parting side walls and continuous front and rear walls, comprising a compartmented open-top box longitudinally, above which a frame for support of a driving mechanism is placed. Impellers, one to a cell, positioned near the bottom, are carried on vertical shafts connected to a driving pulley.

In operation, with the cell full of pulp, feed is introduced continuously and flows into the revolving impeller, whence it is thrown radially toward the walls, and thence starts upward in a roughly spiral path modified by the corners of the cell box. Radial baffles stop the spiraling and prevent vortex formation, so that the body of pulp above them is substantially quiescent as a whole but filled with eddies. The mineral-bearing froth is continuously swept off from the pulp, at the top of the cell, by revolving paddles. It is generally economical practice to float the material that represents the smallest percentage of the batch. This is not always feasible however; if the cost of reagents to float any one material is excessive, it may be cheaper to float the material that represents the largest percentage. The following is a partial list of materials that can be treated by flotation:

Dolomite	Olivine	Sillimanite
Fluorspar	Clays	Spodumene
Gypsum	Corundum	Talc
Magnesite	Feldspar	Tourmaline
Andalusite	Kyanite	Wollastonite
Beryl ore	Mica	Zircon
Brucite	Quartz	Coal

Chapter 21

PROSPECTING FOR CLAY DEPOSITS AND COLLECTION AND PREPARATION OF SAMPLES

As existing clay deposits become depleted, it is necessary to prospect for new sources of raw materials. Many clay deposits outcrop at the surface, or may be seen along river banks and railway cuttings. Others are buried under several feet of overburden and must be discovered by drilling or sinking test pits.

The simplest method of prospecting is by reconnoitering or tramping over the country looking for external signs of a clay deposit. Evidence of a clay deposit may be found in actual outcroppings of the clay on the surface, on hillsides where it has been exposed by landslides, in excavations for buildings, along railroad cuts, and along river banks. The character of the vegetation will also give a clue as to the nature of the ground. Vegetation does not thrive on clay. Clay remains wet for a long time after a rainfall and when it finally does dry, it bakes hard and exhibits shrinkage cracks. This is poor soil to support growth, so that when an area of good vegetation growth suddenly merges into an area of poor growth and farther on once again becomes good growth, it is an indication of the possibility of a bed of clay underneath the region of poor growth.

Springs issuing from the same level or in a straight line along the side of a ridge or hill indicate that below this line is a stratum more or less impervious to water. Water, seeping down through overlying soil, would reach the more or less impervious layer of clay and would then collect until it issued from the side of the hill in the form of a spring. A number of such springs would indicate the line of the clay stratum.

Ponds which remain long after a rainfall are another indication of a possible clay bed. Water would not readily drain away through an underlying bed of clay and would remain on the surface long after other areas had dried out.

Other indications of possible clay deposits require a greater knowledge of geology and mineralogy. A knowledge of the geological history of the country, coupled with the nature of the outcropping rocks will indicate the probability of kaolinization having taken place and the possibility of underlying residual deposits. The geology of the region may indicate the presence of an ancient sea or lake and the possibility of a marine or lacustrine deposit.

When the clay deposit lies deeply buried, the surface indications given do not suffice. Some method of penetrating into the deposit must



Fig. 117. Auger Drill
(Courtesy H. C. Spinks Co.)

be employed. Boring is a type of penetration which consists of drilling a comparatively small hole from the surface to the deposit. Earth or hand augers may be employed for depths of 20 to 25 feet, and under unusually favorable circumstances, a depth of about 90 feet may be reached. Fig. 117 shows an automatic auger drill in operation. Augers with a flattened 2-in. bit attached to sections of pipe are used. The bit is turned by hand or by machinery. When it has penetrated the length of the turns of the auger, it is drawn from the hole and the material clinging to it is removed. This is repeated until the required depth is reached. One unsatisfactory feature of this type of boring is the contamination of the sample with the material from overlying strata. However, this method is comparatively cheap and speedy.

When exploring for a clay deposit with an auger, drill holes are usually drilled in 100-foot squares. Although some pits are smaller than 100 feet in diameter, few pits larger than 50 feet are missed, as one of the four holes in a square usually will contact clay in a pit 50 to 75 feet in diameter. When a pit is located, holes are drilled at 25- or 30-foot intervals. Samples thus taken are unsatisfactory for determining the quality of the pit, for a clean separation of the sample cannot be made. The sample, however, does indicate whether additional drilling or testing is needed.

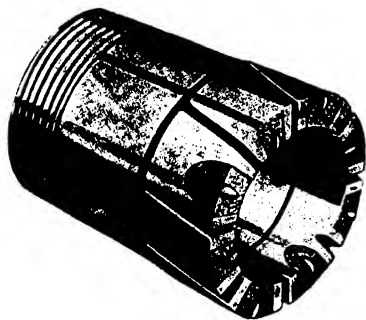


Fig. 118. Diamond Drill Crown Set with Eight Black Diamonds Ready for Use

Diamond core drills, although very costly, have a large advantage over augers with regard to depth of penetration and condition of the sample recovered. Another advantage is that they will penetrate any material, no matter how hard. Diamond drills are made by setting black diamonds in the end of a short length of pipe (Fig. 118). The other end of the drill is joined to a pipe section and others are added as the depth requires. The drill turns or revolves, thereby cutting out a core which rises inside of the pipe. Sections of core are removed from time to time, and by joining these sections, a complete log or cross section of all the strata from the surface to the depth penetrated is obtained.

The sections of core are laid out, as they come from the ground, in a long, sectional core box. Sometimes the cores are split longitudinally, half being retained for permanent record and half being sent to the laboratory for analysis. The cost of diamond drilling is very high, and it should be used only for drilling deposits of potentially high value.

The test-pit method of prospecting is often used for deposits lying beneath the surface. It has the advantage of yielding much better sam-

ples, but the depth of penetration is limited. The pits are dug by hand; one man excavates the material with pick and shovel and another man hoists it out of the pit by rope and bucket, either by hand power or by windlass. The pit is made 30 to 40 inches in diameter, which affords room for operating the tools. Two men can sink a pit 10 to 40 feet per day. If the ground is soft, the sides of the pit may have to be reinforced with timbers. The particular advantage of this method is that the deposit is exposed in such a way that a perfectly satisfactory sample can be obtained and the general character of the deposit can be observed.

The purpose of prospecting is not only to discover the clay deposit, but also (1) to observe the character and amount of the overburden, (2) to observe the thickness and extent of the deposit, (3) to observe the dip and strike of the strata, (4) to observe the drainage conditions, (5) to observe the transportation facilities, and (6) to obtain samples reliably representative of the deposit.

The procedure for preparing the sample varies with the method of obtaining it. If obtained from an auger or diamond drill, the entire section of the deposit constitutes the sample. If it is obtained from outcrops or test pits, the procedure is as follows: An entire section of the deposit from top to bottom is obtained, spread out on a sail cloth and broken down into lumps less than 2 inches in size. It is then quartered down to an amount between 75 and 100 lbs., which is placed in a container and shipped to the laboratory for further treatment. It should be marked with its location and all pertinent information observed in obtaining it. Coning and quartering is done as follows:

- a. The sample is spread out on a coning cloth. The cloth is lifted by two diagonally opposite corners, and the sample rolled and mixed toward the center of the cloth. This procedure is repeated with the two remaining corners of the cloth.
- b. The cone is flattened and divided into four approximately equal parts.
- c. Two opposite quarters are discarded.
- d. The remaining two quarters are mixed and coned according to the above procedure until the desired size of sample is obtained.

In the laboratory each sample is crushed, quartered, and screened until a final sample of about 5 lb., which will pass through a 20-mesh screen, is obtained. This sample is packed in a clean container or tightly-woven sack, labeled inside and out with full information, and signed by the sampler. It is then ready for physical and chemical tests.

The sampling of the clay deposit is very important and must be done with exceeding care and diligence. Upon the results of the testing of samples rests the decision of whether or not to invest thousands of dollars in developing the property. Great financial loss can be avoided for the small cost of careful and accurate sampling. A sufficient number of samples must be taken to insure the extent and uniformity of the deposit. No amount of money spent in sampling a deposit is wasted if undesirable features can be discovered before the plant is built and equipment is purchased.

Chapter 22

PROPERTY SURVEY

The proper development of a clay property is contingent upon a reliable survey having first been made of the property. If the laboratory tests on the clay prove satisfactory and it is decided to attempt development of the property, the first step is to obtain or prepare a reliable land-survey map. The following information must be clearly shown on the map:

1. All property lines, boundaries, and the full extent of the property under consideration.
2. Location of existing buildings, streams, railroad lines, roads, wells, springs, test pits, tunnels, and timber.
3. Adjoining property, so that options may be secured if the deposit proves extensive.
4. Proximity to towns for shipping, labor, and supplies.

The second step is to obtain a topographical map showing contour lines and elevations. Frequently the survey map and contour map are combined as one.

The development of a theoretical property will serve to illustrate the information that can be obtained from a reliable survey. Fig. 119 is an example of what a combined survey and topographical map might look like.

The engineer's report which will accompany this map must answer the following questions:

1. What is the quality of the water?
2. Would it cause scale or scum in the boilers?
3. Is the creek or river capable of generating power?
4. Is either capable of barge transportation?
5. What is the value of the timber?
6. Is there sufficient timber to furnish timber for mine development?
7. Is there any other clay on the property?
8. Is the land sufficiently level and above river to make a safe factory site without expense of drainage and filling?
9. Is the river in the habit of flooding and causing damage?
10. Can the private road be closed, and shut off the shortest route to town?
11. What is the policy of the railroad about taking care of its customers in time of car shortage?
12. Is the property entirely dependent on one railroad?

13. How far would a private line have to be built to connect with a competitive road?
14. Could the right of way be obtained easily?
15. Could the adjoining property be optioned at a reasonable price if expansion is desirable?

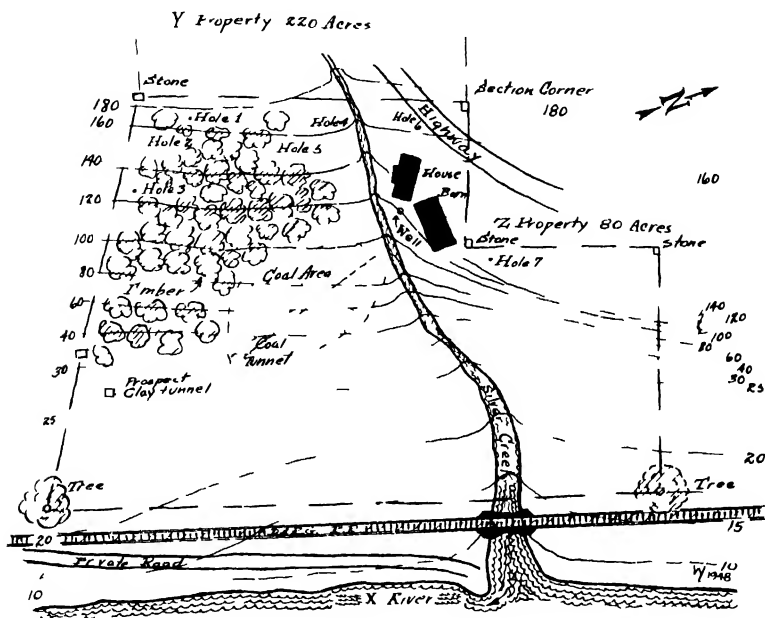


Fig. 119. Survey Map

The engineer's report, we shall suppose, answers the above questions thus:

1. and 2. The well water is pure enough for drinking, but is high in lime and magnesia, and would cause scum and scale in the boilers. The creek water is satisfactory for use in boilers, but is too insanitary for drinking. There is abundant water for year-round operation of a plant.
3. The creek could be dammed to provide power and reserve water for fire protection.
4. Barge transportation would be impractical unless dredging were undertaken.
5. The timber is of considerable value.

6. Yes.
7. Diamond drilling disclosed other clays and high-grade limestone suitable for the production of burnt lime. (See log of drill holes)
8. Yes. A plant can be located at the base of the hill where there is sufficient slope for the drainage.
9. No. It would drain away from the plant.
10. Not once it has been made public.
11. The railroad expressed willingness to cooperate.
12. No. The nearest competitive railroad is seven miles from the property.
13. Seven miles over hilly country.
14. The cooperation of the local chamber of commerce has been obtained and the right of way has been granted free.
15. Options have been obtained.

A log of all drill holes accompanies this report. Fig. 120 is a reproduction of the engineer's log of holes 1 and 6.

At least one cross section through the property (Fig. 121) showing various strata and how they run, will be given.

The engineer's report is carefully studied in conjunction with the laboratory report on the tested clay samples. Suppose that the laboratory report gives the following information:

<u>Material Tested</u>	<u>Results of Tests</u>
Shale 1 - 1	Works well in an auger machine, good plasticity, will not take a salt glaze. Recommended for brick and tile, but not sewer pipe.
Fire clay 1 - 5 1 - 8	This clay forms a strong body between cones 7 and 11, overburns at cone 14. When weathered, it develops fair plasticity and will take a salt glaze. Recommended for sewer pipe.
Fire clay 1 - 12	This clay has a P.C.E. of cone 32, and is a high-grade fire clay. Recommended for first-quality refractories.

After a study of these reports, it was decided to:

1. Buy the property and secure options on the surrounding land.
2. Build a refractories plant and sink a shaft to fire clay 1 - 12.
3. Build a brick plant and utilize the shale.
4. Provide in the plans for a future sewer-pipe plant.

The location of diamond-drill holes, auger-drill holes, or test pits on any property should be laid out systematically. The number of drill holes or test pits will vary with the amount of money available for drilling, but in any case, the holes should not be drilled haphazardly. Information that may be obtained from drill holes is as follows:

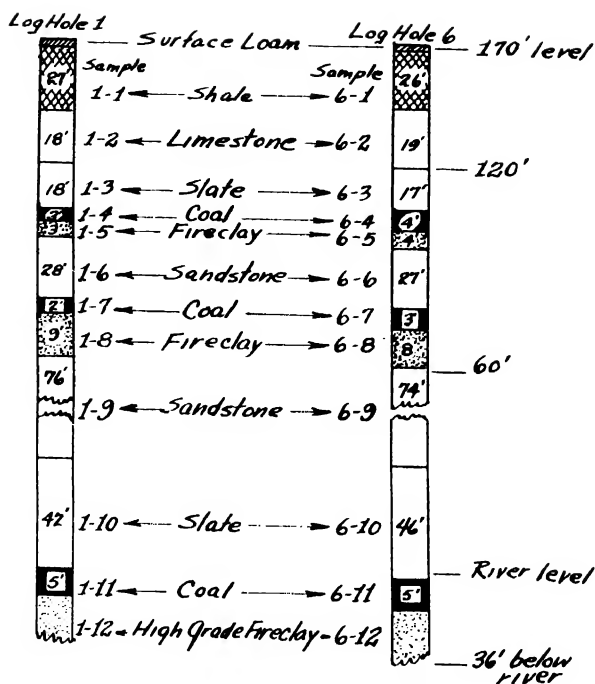


Fig. 120. Log Holes 1 and 6

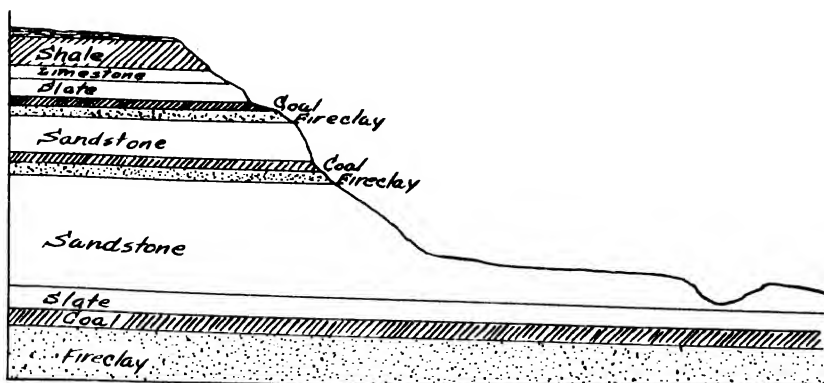


Fig. 121. Section of Clay Deposit

1. Given the pitch of the measures, the amount of overburden that will have to be removed at any place on the property can be calculated.
2. Drilling shows how deep from the surface it is necessary to go to strike any measure.
3. It shows where any body of clay should be opened in order to get the proper drainage.
4. It shows the most economical grades for railroad or truck roads.
5. It gives an estimate of clay lying outside the boundaries of the property.
6. It indicates where to look for outcroppings of the deposit.
7. It shows how drainage systems should be laid out.
8. It shows how far water from streams will seep through.
9. It shows how deep the dry-pan pits can be dug without danger of their being flooded.
10. It shows the grading and filling necessary for any new building.
11. It shows how deep kiln-well holes can be dug without danger of their being flooded.

Chapter 23

WINNING CLAYS

Winning of clays refers to the operations involved in obtaining them from the ground and transporting them to the plant for further processing. There are three general types of winning operations: (1) Superficial — is gathering clays from an open pit, and involves the removal of overburden if necessary. This is the simplest and cheapest method of winning. (2) subterranean — is underground mining of clays. This type of mining is very costly and wasteful, and is resorted to only where the desirable clay deposit is very deep down from the surface and is of high value. (3) Subaqueous — is the winning of clays under water. Subaqueous methods are expensive and are rarely used.

Subaqueous winning is practiced in certain regions like Florida, for mining kaolins. Where low, flat land is surrounded on two or three sides by water, and where the land surface is mostly sand, open pits cannot be dug to any great depth before they will fill with water, and other methods of recovering the kaolin must be resorted to.

One of the simplest methods is to open a large pit with a power shovel and allow it to fill with water. When the pit contains a sufficient amount of water, a large barge is floated on the artificial lake thus created. The barge is equipped with a long flexible hose with a cutter head on one end. The cutter head consists of a series of revolving knives. This is lowered to the bottom of the pit and as the cutter loosens the kaolin it is sucked up through the hose, in the form of a slurry, and pumped into settling tanks on the barge. There the kaolin is allowed to settle, some of the excess water is pumped out, and the remaining kaolin and water is pumped to the plant on shore.

Clam-shell shovels, mounted on a barge, are sometimes used to dig the clay and dump it into the settling tanks.

Subterranean mining of clays is resorted to only when the clay is of high value, and where it is covered by several feet of overburden. Since material overlying a clay deposit must be dug up and transported away from the clay bed area, it is sometimes cheaper to mine the clay underground than try to win it from an open pit. In general, clays can be won most profitably by underground methods when the overburden is more than three times as thick as the deposit to be worked.

Mining methods that have been designed for the mining of coal can be readily adapted to the mining of clays. Whenever underground mining of clays is attempted, the operator should have a sound basic knowledge of principles of hard-rock mining and coal mining. Certain fundamentals apply to all types of underground mining.

The safety of the miners and workmen underground is of paramount importance. Good ventilation and an easy means of escape are the first considerations. Usually two vertical shafts are sunk from the surface of the ground to the seam of clay to be mined. One shaft is for hoisting men and materials to and from the surface, and the other shaft is for ventilation. These are spoken of as the hoist shaft and the air shaft. At the level of the clay seam, horizontal drifts or tunnels are dug away from and at right angles to the hoist shaft, in order to open up a face of the material. Ventilation is obtained by forcing air down the hoist shaft, deflecting it into the proper drifts, and exhausting it up the air shaft (Fig. 124).

Haulageways are those tunnels which lead directly to the hoist shaft. A single haulageway (Fig. 122-a) does not provide an escapeway for the workers in case of a cave-in. As can be seen, a cave-in at any place in the main haulageway will block off other parts of the mine where men may be trapped. The double entry (Fig. 122-b) provides for two horizontal shafts connected at intervals by cross cuts. In case of a cave-in, men can escape to the second shaft and pass around the caved-in portion. This is the most widely used system. The triple-entry system (Fig. 122-c) has three horizontal shafts and insures safety and rapid exit for the men in case of a cave-in.

In driving a shaft or tunnel in a mine, it is necessary to support the walls and roof of the tunnel with heavy timbers to prevent their caving in (Fig. 123). The type of timbering required in any tunnel will depend upon the nature of the material through which the tunnel is being driven. The three types most generally used are:

1. Half-set. If the floor and one wall of the tunnel are composed of hard rock, timbering will be required only to support the weaker wall and roof.
2. Three-quarter-set. Where the floor only is of hard rock, it is necessary to support both side walls and the roof.
3. Full-set. Timbering is required for all four sides of the tunnel where weak or unconsolidated material prevails. This is the usual case in clay mines.

If the roof of the tunnel is of sandstone, limestone, or slate, it will be necessary only to have timbering posts spaced every 10 or 12 feet; but a roof of loose material will require solid timbering. When full-set timbering is used, the car tracks are laid directly on the floor timbers, which act as ties. Drainage is usually taken care of by driving the tunnels so that they slope slightly toward the main shaft. Gutters are dug along side the tracks which carry any surface water to a sump in the main shaft, where it is periodically removed by means of a pump. Lagging is the term applied to the practice of supporting the roof between the timbers. Planks six to ten inches in width are set from wall to wall to support the roof. They are allowed to overlap one another about one inch and are supported by longitudinal beams.

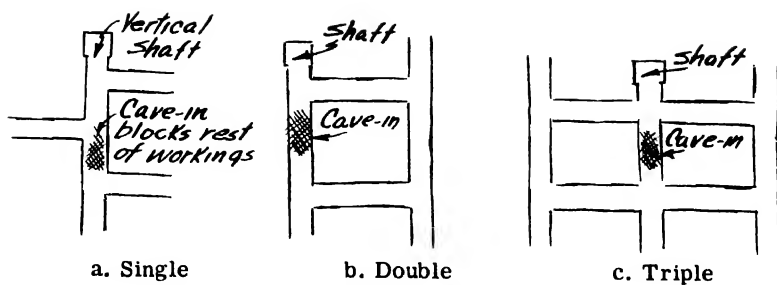
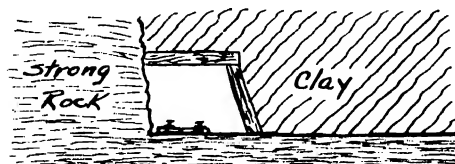


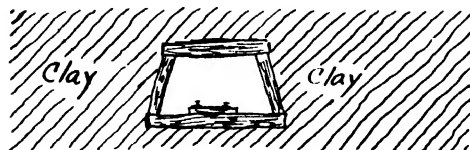
Fig. 122. Types of Entry Shafts



a. Half-set



b. Three-quarter-set



c. Full-set

Fig. 123. Timbering a Mine Shaft

All systems of underground mining are, to a certain extent, wasteful. By no means all of the material can be recovered, as supporting pillars must be left to prevent the roof from caving in. The room-and-pillar system (Fig. 124) provides for high recovery of the material being mined, but cannot always be used in clay mining. In room-and-pillar mining, two shafts, an air shaft and a hoist shaft, are sunk to the level of the deposit. Drifts are dug at right angles to the haulage-ways so as to block the deposit off into a series of rooms. These rooms are then mined so as to recover as much material as possible; however, some of the material must be left in the form of pillars to support the roof. After the rooms have been emptied, charges of explosive are set in the pillars, and the whole room is allowed to cave in. All entries to a room are cross-cut to provide for ventilation and escape.

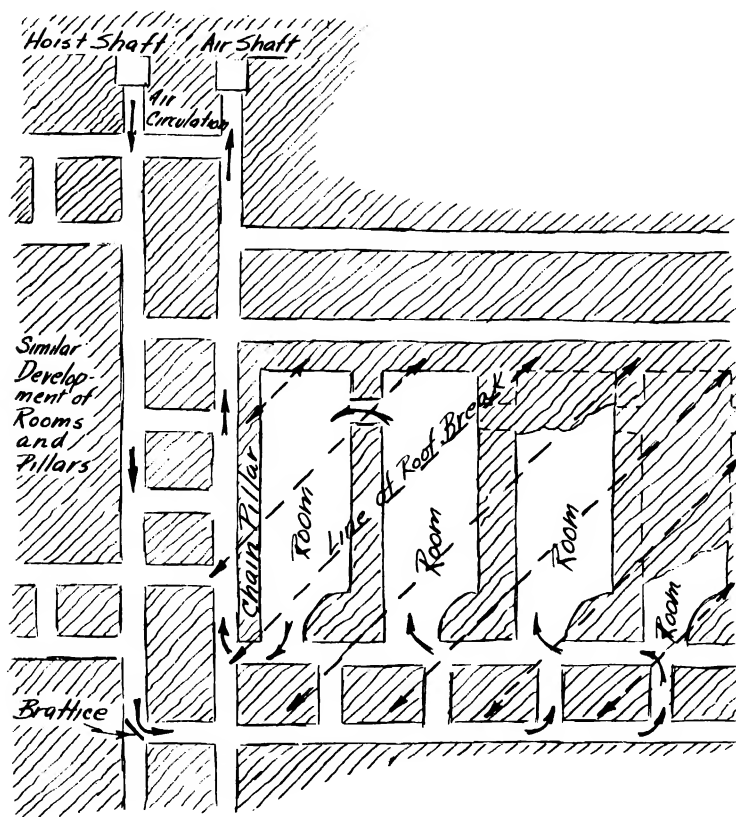


Fig. 124. Room and Pillar Mining

Underground clay seams are seldom found to run in an orderly or systematic fashion. Often the clay strata will have been twisted and folded by geological disturbances. In a mine tunnel, the floor of the

tunnel is spoken of as the "foot wall" and the roof as the "hanging wall." It is not uncommon to find the seam of clay so twisted that it returns and passes under itself, and the foot wall becomes the hanging wall. Obviously, this type of vein could not be worked by the room-and-pillar system. The clay seam would have to be selectively mined and the shaft would follow the angle of the seam. This type of mining is called the block system (Fig. 125). It is inefficient and wasteful, as only 30-40% of the deposit can be recovered.

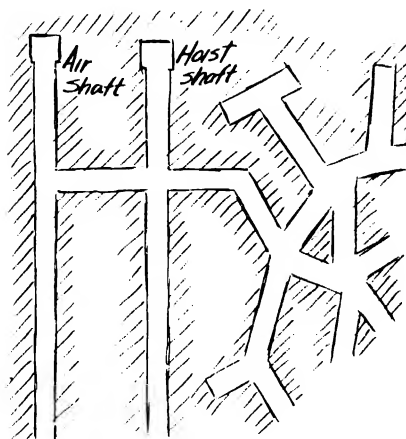


Fig. 125. Block System of Mining

Sometimes a mine-entrance tunnel can be driven in through the side of a hill. This is less expensive than sinking and

maintaining a shaft. Three types of mine-entrance tunnels are shown in Fig. 126.

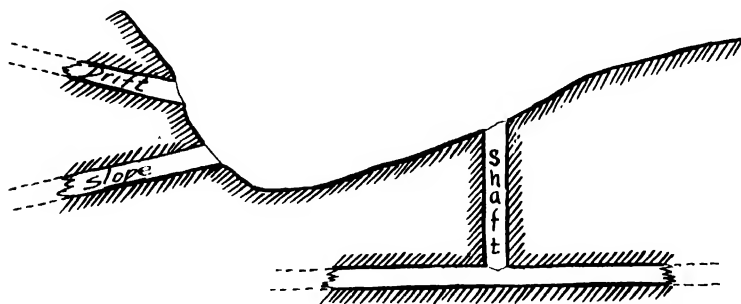


Fig. 126. Mine-Entrance Tunnels

When the entrance of the tunnel is below the vein of clay and the tunnel is driven sloping upward, it is spoken of as a "drift mine." This is the least expensive type of mine entrance. The loaded mine cars are brought to the entrance of the mine by gravity, and only empty

cars need be hauled upgrade. When the entrance is above the clay deposit and when the tunnel is driven into the side of a hill and sloping downward toward the deposit, it is known as a "slope mine." This type of mine requires hauling the loaded mine cars to the mouth of the mine, and empty cars are returned by gravity. A "shaft mine" is one in which the deposit is far below the surface of the ground and entrance is obtained by means of a vertical shaft. This is the most expensive type of mine to operate.

The size of mine tunnels will depend upon the size of the workings. The most efficient size of mine car is one with a width of from four to four and a half feet, and, to accomodate this size car, the tunnel must be at least six feet wide. Most tunnels are eight feet in width, since the narrower tunnel increases the resistance to flow of ventilation air due to increased friction, and requires more powerful fans to effect good ventilation. The height of the tunnel need only be sufficient to accomodate the average man.

Blasting is usually necessary in order to loosen the material and advance the working face. Blasting standards as set by the U. S. Bureau of Mines must be followed. The three classes of explosives specified are as follows:

<u>Class</u>	<u>Gas Liberated per 1 1/4" x 8" Cartridge</u>
1	Less than 0.16 cu. ft.
2	0.16 to 0.33 cu. ft.
3	0.33 to 0.67 cu. ft.

Classes 2 and 3 are permissible for underground use only when proper ventilation is provided.

In blasting hard rock, the best type of explosive would be one that would give a shattering effect to the rock and break it into small pieces, but for clays it is more desirable to use an explosive with a pushing rather than a shattering action. In this case, large blocks of clay are pushed away from the working face and the clay is not scattered about as fine particles.

Black powder is a cheap blasting material and does a good job, but it generates too much poisonous gas and so cannot be used. The best type of explosive is one which generates very little gas, is moisture resistant, and is safe to handle.

Nitroglycerine is easily detonated and too sensitive for safe handling. It generates a large volume of poisonous gas, has a smashing effect when exploded, and is immune to moisture. It is not the best explosive for blasting clays.

Ammonium nitrate is the most commonly used explosive for clays. It has a slow, heaving effect when exploded; it is safe and hard to detonate; it has a good spreading action; it has the least amount of objectionable fumes; but it has very little resistance to moisture.

Gelatin dynamite is nitroglycerine dispersed in cotton. It is resistant to moisture, has a moderate smashing effect, and is moderately hard to detonate.

Detonation is accomplished by two general methods. (1) **Fuses and Blasting cap.** A detonating cap is affixed to the end of each cartridge and the cartridges are placed in blasting holes previously drilled into the ore body. A slow-burning fuse is attached to the detonating cap of the last cartridge to be placed in each hole, and the remainder of the hole is filled with packing material to the face of the working (Fig. 127-a). The blasting caps contain fulminate of mercury. The fuses are slow-burning, and the length of fuse determines the time that will elapse between the lighting of the fuse and the explosion of the cartridge. (2) **Electric squib.** Detonators are affixed to the cartridges and cartridges are placed in the drill holes as in the previous method. In place of fuses, long electric wires are attached at one end to the detonating cap of the outside cartridge in the drill hole, and at the other end to a hand-operated magneto box. To set off the explosion the operator, from a safe distance, plunges down the handle of the magneto box, thereby generating an electric current which explodes the cap and cartridge (Fig. 127-b).

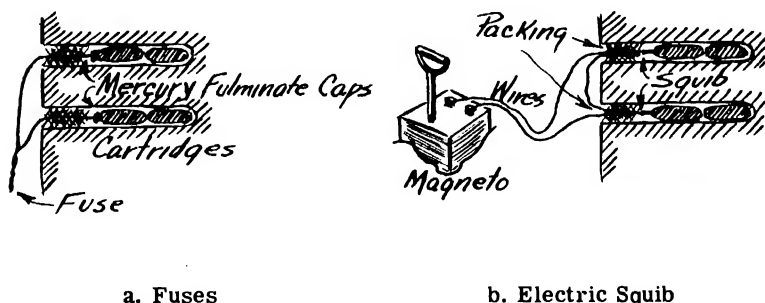


Fig. 127. Method of Detonating Explosives

Drill holes must be placed in the working face of the mine so that the explosive can most effectively break down the working face. Drill holes are usually about 6 feet deep and from 1 1/4 to 2 inches in diameter. Holes drilled on the outside of the face nearest the side walls should slant toward the side walls, and those drilled at the top of the face should slant toward the roof. This tends to advance the working face in a uniform manner, and keep it running in a straight line and on the same level. Holes may be drilled by a hand auger, a pneumatic drill, or an electric drill. The electric drill is the type most often used.

The hand auger⁸ is too slow and the pneumatic drill tends to become clogged with clay. An electric drill will drive a hole at the rate of about one foot per minute, as compared to one foot in five minutes for the hand drill. The general practice is to do the drilling and placing of cartridges at such a time that the firing may take place when most of the workmen are out of the mine.

The majority of clays are won by open-pit or superficial methods. Open-pit mining is the least costly method of all and for this reason, all common clays of low value are won by this method. It has the following advantages over underground mining:

1. The entire deposit can be removed. In underground mining, pillars of valuable clay must be left to support the roof.
2. No timbering is required. The cost of timbering a mine adds considerably to the cost of mining.
3. There are no underground workings to keep open, drained, and ventilated.
4. There is no danger to the workmen from cave-in of the workings.
5. There is no danger of fire.
6. There is no artificial lighting to maintain.
7. The open pit provides a larger working face.
8. A larger area can be blasted at one time.

Disadvantages are:

1. The expense of removing overburden.
2. The entire deposit is exposed to the weather. During a rainy season, the clay becomes soaked with water and is difficult or impossible to dig. Pits often become filled with water and have to be drained.
3. The variable water content of the clay, due to weather conditions, makes the clay difficult to handle in the forming machinery. If the clay is too wet, it has to be partially dried before it can be pugged. If it is too dry, sufficient water must be added at the pug mill to obtain the desired plasticity.

If the clay is not exposed to the surface, but is covered with some type of overburden, the overburden must first be stripped away. The depth of overburden may vary from a few inches to twenty feet. Stripping may be done (1) by hand, with a shovel and wheelbarrow. This method is feasible only when the deposit is small and the overburden is light. (2) Plow and scraper. If the overburden is not too deep, it can be readily loosened with a plow and removed by means of a horse- or tractor-drawn scraper. (3) Power shovel. The use of a power shovel for a stripping operation is economical when there is a considerable amount of overburden on an extensive clay deposit.

After the removal of the overburden, the clay itself must be dug and transported to the plant. Clay deposits are not always homogeneous from top to bottom, but the variations of sandy material and pebbles

are usually fairly well defined and the pit can be worked accordingly. Beds of clays vary considerably in thickness and quality. Deposits may be eight feet deep or more, but often two or three feet is the limit that can be used, as the clay changes in character and composition.

The simplest method of excavation is by man power with a pick and shovel. This method is used only where the plant has a very small capacity, and not much clay is required each season. It has the advantage in that expensive excavating machinery is not standing idle many months of the year. The use of animal power reduces the labor costs and allows a larger tonnage of clay to be dug per unit cost. The surface of the deposit may be loosened by means of a horse and plow, and the loosened clay is then picked up with a horse-drawn scraper. The scraper load of clay is hauled to a dumping platform where it is dumped through a hole in the platform into a waiting clay car. Scrapers are adaptable where close control of the material used in the manufactured product is not essential and used mostly on unconsolidated terrace-plain clays. If the deposit is non-uniform, it should be worked on a slope (Fig. 128), so that the various layers of clay will be fairly well mixed when delivered to the plant. For haulage distances over 100 feet, it is better to use a wheeled scraper. Scraper buckets will hold between 3 and 7 cubic feet of clay. In place of a scraper, a clay gatherer is often used. The clay gatherer is a horse- or tractor-drawn machine which picks up loosened clay as it is drawn across the deposit, and carries it in a steel drum. When full, it hauls the clay to a loading platform or directly to a stock pile. This type of machine develops a working that exposes a larger area to the elements; as the digging done is shallow, there is necessarily a great expanse of ground under operation. The bite is small, and the gatherer is dragged about 30 feet before it is loaded. It gives horizontal mixing of the deposit. This particular type of equipment is suitable to level and slightly rolling country, and is of particular advantage in clay operations where weathering is desirable. The clay may be dug by other means and spread out over the surface of the ground to weather for a season. This clay may then be easily picked up by the clay gatherer and transported directly to the plant. One man and a team can load the 18-cu. ft. hopper of a clay gatherer in 30 to 60 seconds. It is usually used on small operations, but may be used as auxiliary equipment on large operations.

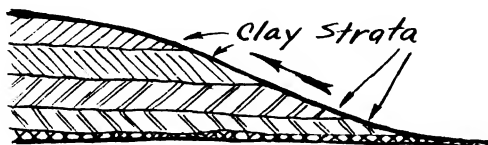


Fig. 128

The power shovel (Fig. 129) is the most general type of excavator used for clays. It can be used to remove overburden as well as to dig clays, and can be used on any kind of clay, wet, or dry, or clay containing boulders. Shales and flint clays must first be loosened by blasting. Its particular value lies in its capacity for work and its flexibility of movement. There are four types of power shovel:

1. Steam shovel. Disadvantages of the steam shovel are:
 - a. Steam must be kept up whether it is in use or not.
 - b. Fuel and water must be transported to the machine.
 - c. Two men are required to operate the steam shovel.
 - d. In winter the water lines are in danger of freezing.
2. Gasoline shovel. The gasoline shovel is more easily handled and can be operated by one man.
3. Diesel shovels and gasoline shovels are the most economical.
4. Electric shovel. This shovel can also be operated by one man, but requires that electric power lines be extended to the pit.



Fig. 129. Power Shovel
(Courtesy the Thew Shovel Co.)

Power shovels may have different types of locomotion. They may be mounted on a barge and used for digging clay from the bottom of a lake. They may be mounted on railroad tracks; or they may be mounted on caterpillar treads. The use of caterpillar treads gives the shovel its greatest flexibility.

The dipper-stick type of bucket is most common. For digging clays, the size of bucket usually used will range from $3/4$ cu. yd. to $1\ 1/4$ cu. yd. One shovel can dig up to 700 cu. yd. of clay a day. This is generally in excess of what most plants can use.

The power drag scraper is a powerful excavator and a rapid conveyor. The equipment consists mainly of a Crescent bottomless scraper bucket (Fig. 130) attached by front and rear bridle chains to two long wire cables, one known as the load cable and the other the backhaul cable, which wind and unwind on the drums of a two-drum hoist. At the head end of the installation, both operating cables pass through guide blocks attached to a head-frame or mast. At the rear end of the installation, the backhaul cable passes around a movable tail block (Fig. 131). As the bucket is dragged across the deposit, it picks up a load, which is conveyed to the dumping tower. The tail tower is movable and the line of operation can be shifted over a wide area without changing the location of the dumping tower. The amount of material removed depends on the length of the haul. For a $3/4$ yd. bucket, over an 800- to 900-ft. haul, 25 to 33 cu. yd. can be removed per hour. From 3 to 5 acres can be worked before it becomes necessary to move the dumping tower to a new location. The drag line can excavate to a depth of approximately 100 feet. It is able to show low cost per cu. yd. of materials excavated, hauled, and placed, owing to its low first cost and its economies in operation. It has the following advantages for digging clay:

1. It can be used in wet pits and even for digging materials under water where the lake or pond can be spanned by the tail and dumping tower.
2. It hoists the clay out of the pit, thereby eliminating hauling machinery or cars in the pit.
3. It gives horizontal mixing.
4. It has a low first cost and low operating cost.

It is limited in its application in that it can be used only on fairly soft, unconsolidated clays.

The shale planer (Fig. 132) is a machine for cutting and scooping up shale or clay from the solid bank. Cutting tools are mounted on a chain which runs over the cutting boom. When the cutter chain is brought into contact with the clay bank, the cutter bits plane off material in small cubes, from top to bottom. The material falls into a boot at the bottom of the cutting boom from where it is transported by a drag conveyor to a trailed hopper for pit car or truck loading. Planers are either rail mounted or crawler mounted. The cutting



Fig. 130. Crescent Bucket
(Courtesy Sauerman Bros. Inc.)

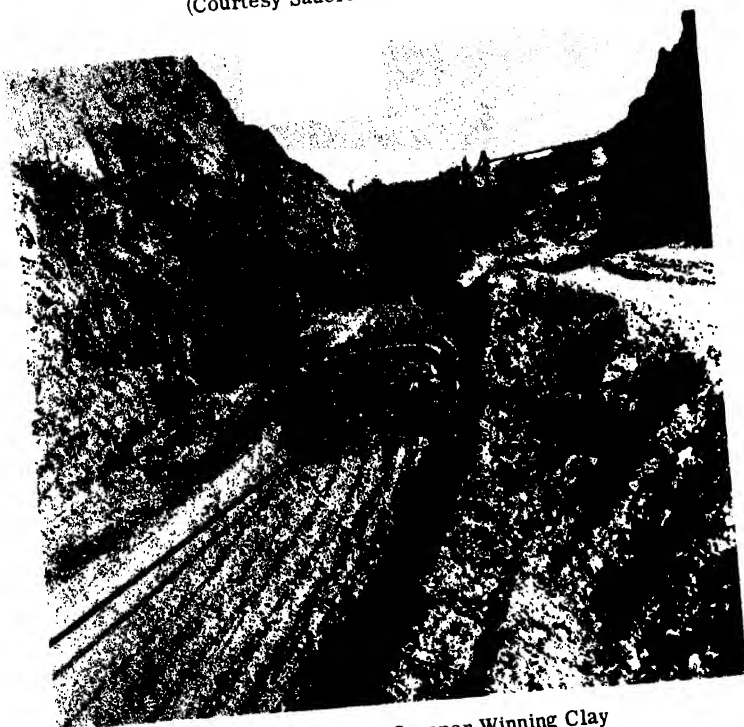


Fig. 131. Dragline Scraper Winning Clay
(Courtesy Sauerman Bros. Inc.)

swing cycle is controlled from a panel in the operator's cab. The depth of cut into the bank is also controlled electrically, thus insuring a uniformity of cut.



Fig. 132. Shale Planer
(Courtesy Eagle Iron Works)

The cutting tools plane a shallow cut through every stratum, dropping the material, as it is planed, into the conveyor buckets below. Fully half of this mixture will pass 1/2-inch mesh and practically all will pass 1 1/2-inch mesh. A standard excavation taking a 50-foot cut into a shale bank has a capacity of 50 tons per hour of continuous service.

Advantages of the shale planer are:

1. No large chunks to crush can come from a shale planer. Much of the material can go to the pug mill directly without preliminary crushing.
2. There is no clay or shale lying in a pit to become soaked up during wet weather.
3. There is practically no frozen material to grind in winter.
4. The shale planer gives uniform mixing from top to bottom of the bank.
5. The power consumption of the machine is very low.
6. Because of the small amount of material exposed to weather in the face being worked, the initial moisture is kept in and better pugging qualities are obtained.

Disadvantages are:

1. It develops a high face which gives opportunity for shale slips.
2. It is not very flexible.
3. It is a difficult machine with which to open a deposit.

The dragline excavator (Fig. 133) consists of a long boom, attached to a power shovel base, with a bucket suspended from the end of the

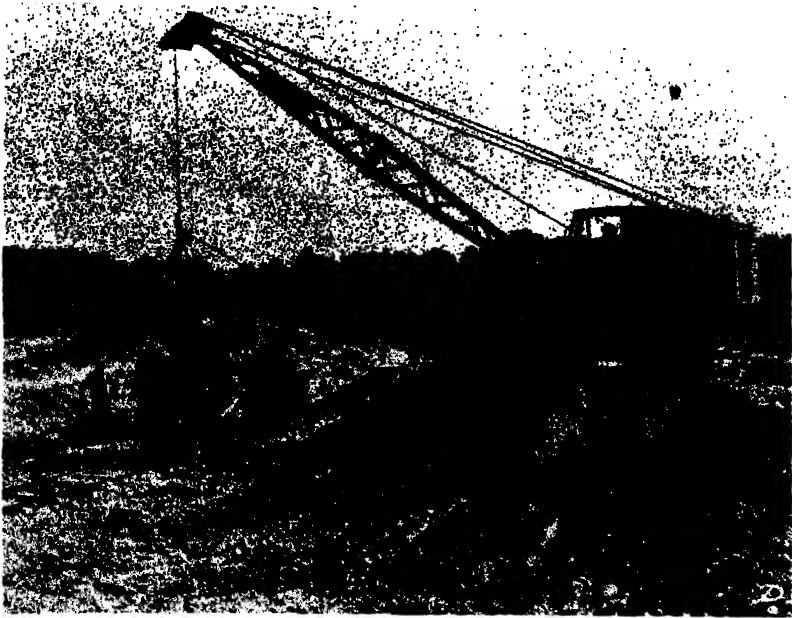


Fig. 133. Dragline Excavator
(Courtesy the Thew Shovel Co.)

boom over the pit. The bucket is dropped to the floor of the pit and dragged across the pit, by means of a cable wound on a drum in the cab of the excavator, until it becomes filled with clay. The loaded bucket is then elevated by the boom and cable and dumped into a car or truck. This type of excavator is also applicable to the stripping of overburden. An excavator with a 100-ft. boom can dig enough clay from a 25-ft. bank to make 85,000 building brick a day. This includes stripping 15 feet of overburden.

SUBJECT INDEX

A

Ageing, 71, 72
 Agitators, 92, 93
 Air separation, 53, 140
 Albany slip, 75
 Allophane, 17
 Amphibole-pyroxenes, 18
 Andalusite, 12
 Angle of nip, 121, 123, 126
 Antimony oxide, 12
 Ashley dye test, 38
 Atterberg test, 37

B

Babcock-Schultz elutriator, 52, 53
 Ball mill, 132, 134, 135, 136, 137, 138, 148, 149
 Consistency of charge, 137, 138, 139
 Flint pebbles, 136
 Media charge, 135, 137, 139
 Media size, 137
 Speed, 137
 Tumbling media, 135
 Zircon ball, 135
 Ball-tube mill, 132
 Barium carbonate, 12, 70, 71
 Barium chloride, 70, 71
 Barium sulfate, 70
 Batch mill, 139
 Bauxite, 5, 12, 17
 Bentonite, 10
 Beryl, 11
 Binders, 13
 Bingham plastometer, 39, 40
 Biotite, 18
 Bischof test, 45
 Blasting, 198, 199
 Blungers, 90, 92, 93, 149, 155
 Bonding power, 45
 Bone ash, 11
 Borax, 12
 Brownian movement, 32
 Buhr mill, 131, 132

C

Cadmium sulfide, 13
 Calcite, 19, 26
 Carbon, 19, 82, 84
 Chert, 18
 Chromite, 12
 Chromium oxide, 13
 Clark viscosimeter, 44, 45
 Classification, laws of, 106
 Classifiers, 106
 Air, 140, 142
 Horizontal-current, 106, 109
 Hydro, 109
 Rake, 107
 Spiral, 108
 Vertical current, 106, 107, 110
 Clay
 Ball, 1, 3, 4, 7, 73, 90, 116
 Bedded, 5
 Bentonite, 33
 Chemical composition, 7, 8, 9, 22, 25
 Classification -Ries, 1
 Colluvial, 1, 2
 Common, 9, 74
 Estuarine, 2, 3, 75
 Fire, 1, 4, 8, 73, 90, 116
 Flood-plain, 1, 5
 Glacial, 2, 3, 5
 Kaolin, 1, 2, 3, 4, 6, 73, 74, 85, 90, 106, 116, 155
 Lacustrine, 1, 3, 74
 Loess, 2, 5
 Low refractory, 4
 Marine, 1, 2
 Mineralogical analysis, 19, 20, 22, 23, 24
 Residual, 1, 2, 3
 Shales, 1, 4, 5, 74, 116
 Transported, 1, 2
 Clay gatherer, 201
 Cobalt oxide, 13
 Colloids, 31, 32, 33, 36, 78
 Color reactions, 20
 Comminution, principles of, 116

Compressibility test, 39
 Compressive strength, 48
 Coulomb viscosimeter, 43, 44
 Copper oxide, 13
 Corundum, 13
 Cristobalite, 85
 Crushers, 117
 Cone, 123
 Conical roll, 129
 Gyratory, 121, 123
 Jaw, 118, 119, 120, 121
 Roll, 125, 126, 127
 Single-roll, 123, 125
 Cryolite, 12
 Cutters, 170, 172

D

De-airing, 167, 170, 174, 175
 Deflocculation, 36
 Diaspore, 5, 12, 17
 Diatomaceous earth, 13
 Dies, 167, 172, 177
 Differential thermal analysis, 20
 Dolomite, 12, 19
 Dragline, 206
 Drag scraper, 203
 Drilling, 186, 190, 192, 199
 Dryers,
 Automatic control, 80
 Direct heat, 79
 Infrared, 80
 Tunnel, 80
 Waste heat, 79, 80
 Drying, 76
 Evaporation pressure, 76, 77, 78
 Humidity of drying air, 77
 Hygroscopic water, 78
 Pore water, 78
 Shrinkage water, 78
 Dry pan, 129, 130
 Dry-press, 158, 174, 175, 177
 Dumortierite, 13

E

Efflorescence, 69, 83
 Electric ear, 148

Electron microscope, 20
 Elutriation, 49
 Extrusion, 165, 177

F

Feather edging, 166
 Feeders, 144
 Constant-weight, 146
 Continuous bucket, 144
 Disc, 145, 146
 Raymond, 145
 Reciprocating plate, 144
 Screw, 145
 Vibrating, 145
 Feldspar, 10, 17, 22, 116
 Filter, drum, 157
 Filter, press, 157
 Firing, 82
 Dehydration, 82, 83, 84, 85
 Oxidation, 82, 84, 85
 Vitrification, 82, 85, 86
 Flint, 10
 Flocculation, 36, 157
 Flotation, 181, 182, 183
 Fluorspar, 12
 Fusion, 61

G

Gelatin, 13
 Gibbsite, 17
 Grinder, 130, 131
 Gypsum, 19, 25

H

Halloysite, 17
 Hammer mills, 129
 Hand molding, 162, 163
 Hematite, 18
 Holdcroft thermoscope, 66

I

Illite, 17
 Ilmenite, 18, 112
 Iron oxide, 13, 84

- J**
- Jackson-Purdy surface factor, 56, 57
- Jigging, 160, 161, 162
- K**
- Kaolinite, 3, 16, 25, 26, 82
- Kilns, 82
- Continuous, 87
- Continuous chamber, 88
- Downdraft, 87
- Periodic, 87
- Scove, 87
- Tunnel, 88
- Kyanite, 12
- L**
- Laminations, 166
- Lawning, 94
- Lead oxides, 12
- Lepidolite, 11
- Lime, 11, 25
- Limonite, 18, 84
- Ludwig volumeter, 58
- M**
- MacMichael viscosimeter, 45
- Magnesite, 12, 19
- Magnetic separators, 112
- Dings, 112
- Frantz Ferro-filter, 113
- Induced-roll, 114
- Magnetic pulley, 113
- Magnetite, 18, 112
- Manganese oxide, 13
- Marriott viscosimeter, 40, 41, 42
- Mica troughs, 90, 106
- Mining, 193, 194, 196, 197, 198
- Mixers, 149
- Clay mixer, 149
- Lancaster, 149
- Ribbon, 152
- Sturtevant, 152
- Mobility, 39, 40
- Molecular formula, 27, 28, 29
- Montmorillonite, 17
- Mullite, 85
- Muscovite, 18
- N**
- Nepheline syenite, 10, 116
- Nickel oxide, 13
- O**
- Olivene, 12
- Open-pit mining, 200, 201
- P**
- Petrographic microscope, 20
- Pholerite, 17
- Plaster of paris, 13
- Plasticity, 34, 35, 36, 37, 38, 39, 40
- Porosity, 57, 58, 94
- Potassium dichromate, 13
- Prospecting, 184, 187
- Pug mill, 152, 154, 167
- Pycnometer, 55, 56
- Pyrite, 19, 25, 84
- Pyrometers, 67, 68
- Pyrometric cones, 61, 62, 63, 64, 65, 66
- Pyrophyllite, 11
- Q**
- Quartz, 17, 25, 85, 86, 90, 116
- R**
- Rational analysis, 20
- Repress, 177
- Ring-roll mill, 132
- Rod mill, 139
- Rouge, 13
- Rutile, 13, 18

S

Sampling, 187
 Sand, placing, 13
 Sand wheel, 90, 157
 Sawdust, 13
 Schoene elutriator, 51, 52
 Schurecht volumeter, 58
 Screening, 49, 94
 Screens, 49, 95, 99, 100
 Punched metal, 95
 Revolving, 98
 Stationary, 98
 Suspension, 105
 Tyler standard, 49, 95
 U. S. standard, 49, 95
 Vibrating, 98, 100, 101, 103, 105
 Screw press, 177, 179
 Scumming, 69, 70, 71, 84
 Sedimentation, 53, 106, 155
 Seger volumeter, 58
 Sewer pipe press, 172, 173, 174
 Shale planer, 203, 206
 Shovel, power, 193, 202, 203
 Shrinkage, 58, 59, 60, 61, 86
 Siderite, 19, 84
 Sillimanite, 12
 Slaking, 48
 Slip casting, 158, 161, 162
 Sodium silicate, 13
 Soft-mud, 158, 163, 164, 165
 Specific gravity, 54, 55, 56
 Spodumene, 11
 Stiff-mud, 158
 Stokes' Law, 53
 Stormer viscosimeter, 42, 43
 Strength test, 39
 Subaqueous winning, 193
 Sulfur, 19, 69, 70, 82, 84
 Survey, 188

T

Tabletting machine, 179
 Talc, 11

Tempering, 152
 Tensile strength, 46, 47, 48
 Test-pit, 186, 187, 190
 Texture, 48, 167
 Thickener, 157
 Throwing, 159
 Topaz, 12
 Transverse strength, 47
 Tridymite, 85
 Turning, 162

U

Uranium oxide, 13

V

Vanadium oxide, 13
 Vapor pressure, 76, 77
 Veritas ring, 66
 Vermiculite, 13
 Viscosity, 39, 40, 62
 Volumeters, 58

W

Washing clays, 90
 Watkin's heat recorders, 66
 Weathering, 71, 72
 Wedgewood pyroscope, 66
 Wedging, 159
 Wet Pan, 154, 162

X

X-ray, 20

Y

Yield value, 39, 40

Z

Zircon, 11

